An archaeometallurgical study of iron production in Ban Kruat, lower Northeast Thailand

Technology and social development from the Iron Age to the imperial Angkorian Khmer period (fifth century BC – fifteenth century AD)

Pira Venunan

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I, Pira Venunan, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis

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Signature:

Abstract

Iron has long been regarded as a crucial element facilitating at least two key activities at the centre of the economic and political history of lower Northeast Thailand from the Iron Age (500BC-AD500) to the fall of Angkor in AD1453: agriculture and construction of water conservation. Both sectors are thought to have been mechanisms manipulated by local and regional elites to generate and maintain wealth and power. Building upon this claim, iron production may have also had a major socioeconomic role in society. However, despite many side references to the abundance of iron-related remains in the archaeological record, little is known about the primary production of iron and its spatial distribution in this region, and the evidence has rarely been explored to its full potential to construct arguments from a technological and craft production point of view.

To better our understanding of this industry and its role in the broader cultural landscape of lower Northeast Thailand, this thesis focused on iron production remains. Slag, technical ceramics, and laterite fragments (possible ore) found at slag deposits in Ban Kruat in Buriram province, and broadly dated from the Iron Age to the Angkorian Khmer period, were analysed. The aims were to reconstruct the *chaîne opératoire* of Ban Kruat ironmaking technology, and to use these technical with broader archaeological and historical knowledge to discuss the environmental and social embeddedness of iron and iron making in the regional setting of lower Northeast Thailand. Archaeometallurgical approaches were employed to extract relevant data from the finds, which were then discussed in social terms with the aid of conceptual frameworks from the social construction of technology and craft production.

The results indicate that the whole production landscape was built upon very similar ironmaking practices, resulting in very comparable production waste and debris. The said process involved the smelting of locally available iron and alumina-rich laterite ores inside shaft furnaces under unusually high temperatures and reducing atmospheres, possibly leading to the direct production of carbon-rich iron. The low technical variability of this practice may have been critically constrained by the ore chemistry that forced the smelting practice to be formulated in such a way in order to win metallic iron from the peculiar ore available. This rendered this technology rather resistant to change or improvement, in spite of the profound changes taking place concurrently in lower Northeast Thailand, ranging from the political (chiefdoms, early state, and the empire) to the socioeconomic (community-based specialised production to Angkorian temple-based economic system).

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Chapter 1 Contexts and layout of the thesis

Southeast Asia is a vast yet comparatively under-researched extremity of the Eurasian landmass, comprising the junction between South and East Asia and the Pacific. In the context of Southeast Asia, regional archaeological research is largely divided into two major geographical zones: mainland Southeast Asia and Island Southeast Asia (Figure 1.1). The present study concerns only on one of the well-researched areas in mainland Southeast Asia: lower Northeast Thailand (Figure 1.2). Over the past 40-50 years, a series of surveys and excavations focussed on this area have generated archaeological data from which our understanding of Thai and mainland Southeast Asian archaeology has grown substantially. The data increasingly depict the region as undergoing important socio-political changes since the early second millennium BC with new ideologies and technologies being introduced by internal and external sources and selectively adopted and/or adapted by local populations (see Chapter 3). Many factors lie behind the transformation of the societies in lower Northeast Thailand from egalitarian to complex state-level. Agriculture, social interaction, and exchange of ideas and goods at various scales are considered influential driving forces. However, this research is based on the premise that another equally crucial player, and one that has received remarkably little attention, is technology, in particular ferrous metallurgy. Of the various metals used since late Prehistory, iron arguably retained a major role, linked to socioeconomic developments by facilitating the intensification of agriculture and the construction of water conservation (c. 6/500BC-AD5/600) (Boyd and Chang 2010; Higham and Thosarat 2012, 167-168; see discussion in sections 3.2 and 3.3.2). These two intensive activities saw the management and mobilisation of resources and labour on unprecedented scales and are thought to have been considered political strategies by local elites to accumulate wealth (O'Reilly 2014). Iron was an essential resource for local populations and became one of the motivations for the settlement expansion to the uplands in order to seek new sources of iron (Moore 1988; Welch and McNeill 1991; see a discussion in section 3.2). In the early historic period (6^{th}-10^{th} century AD) that saw the rise and fall of small polities in lower Northeast Thailand and Northwest Cambodia (Wolters 1974; Vickery 1998), iron had presumably preserved its high value in the socioeconomic and political realms, particularly needed for intensified agriculture and conflicts. During the course of the Angkorian Khmer Empire, a large 9^{th}-15^{th}-century-AD polity that also integrated lower Northeast Thailand as its indispensable territory, iron was more heavily exploited, as inferred by large quantities of iron being offered to the temples and consumed by civic and military activities (Hendrickson and Evans 2015; Pryce *et al*. 2014; to be discussed in sections 4.3.2).

Figure 1.1 Map of mainland Southeast Asia (dark blue) highlighting lower Northeast Thailand (red)

(Image: http://www.un.org/Depts/Cartographic/map/profile/seasia.pdf)

Owing to the aforementioned, the material record may reflect an intimate relationship between iron and socioeconomic domain. This metal was closely bound with fundamental activities for the societies, including agriculture, construction, and warfare. Just as metallic iron had its vital role, its production was also a very significant milieu for technological and economic developments. The organisation of iron production was an inextricably embedded to broader social structures, and for the Angkorian period (AD802-1453), there is strong evidence that wealth and power were acquired through control of the industry (Lustig 2009; Pryce *et al.* 2014; see section 4.3.4.1).

Figure 1.2 Location of Ban Kruat (red star) in lower Northeast Thailand (black dashed lined box)

(Image: http://www.un.org/Depts/Cartographic/map/profile/thailand.pdf)

This importance of pre-industrial iron to explain the social development of lower Northeast Thailand from the Iron Age period onward has often been noted (e.g. Higham 1989, 234-235; Higham and Thosarat 2012, 167; Nitta 1996; Welch 1989, 1998). Typically, this point is illustrated with reference to the abundance of iron artefacts in the region, as well as with somewhat superficial mention to production remains (see a discussion in section 4.3). However, this thesis contends that previous scholarship on the subject is largely constructed upon preliminary, generalising examinations of the evidence, which often simplified and overlooked the technological and social complexity of iron production. Our understanding of iron technologies in Thailand is largely built upon a few sites and overwhelmingly biased towards iron artefacts; themselves rarely studied in detail (see a discussion in length in Chapter 4). Iron production has rarely been fully investigated and contextualised under the concepts and approaches of archaeometallurgy, anthropology of technology, craft production, and political economy in order to construct arguments for past societies from a technological and craft production point of view. Moreover, issues concerning the technological diversity, organisation of production, and the relationship between various production workshops over time and across space have rarely been taken into account.

The production of iron is a process shaped by both physicochemical and socio-cultural factors. Even allowing for important environmental and thermodynamic constraints, there are numerous pathways by which iron can be extracted, which vary across space and time. Iron technologies are adapted and transformed within environmental/thermodynamic/social constraints to fit particular social contexts, and thus understanding how this technology performed and was organised allows archaeologists to gain insight of past societies. This has been demonstrated by many archaeometallurgical studies concerning iron production elsewhere in the world (e.g. Cleere 1981; Bray 2006; Charlton *et al*. 2010; Geselowitz 1988; Gordon and Killick 1993; Iles 2011; Joosten 2004; Veldhuijzen 2005; see Bulbeck and Caldwell 2000; Nitta 1991, 1996, 1997; Pryce *et al.* 2011; Pryce *et al*. 2014 for local applications of this approach to ferrous archaeometallurgical remains; see Brumfield and Earle 1987; Costin 2005; Hirth 1996; Killick and Fenn 2012; Martinón-Torres and Killick 2015; Smith 2004 for broader discussion). If iron production is systematically investigated and contextualised, the data obtained can be used to characterise various engineering and technical parameters of ironmaking recipes and traditions (e.g. production components, smelting mechanisms, technical variability, efficiency, scales of production, and control/standardisation of the processes and products). From these technical data, inferences can be made about social aspects of technology. Combining both technical and archaeological data, technical traditions can be characterised and explained in socioeconomic terms.

This thesis comprises of an archaeometallurgical investigation of iron production remains in the Ban Kruat area, located at Buriram province on the southern edge of lower Northeast Thailand (Figure 1.2). The surveys and excavations conducted by the Thai-Cambodian Living Angkor Road Project (hereafter LARP) in 2005-2010 unveiled enormous quantities of metallurgical material culture, namely 60 slag deposits and other metallurgical components related to iron production. This makes this collection arguably the largest of its kind found in Thailand. Previous pilot studies on a single slag site suggested that it derived from bloomery iron smelting, and that local laterite could have been used as an ore (Venunan 2011; Yoopom 2010; see discussion in sections 4.3.3.3 and 7.2.4.1). Archaeologically, this single site was suggestively affiliated with the Angkorian period (AD802-1453) with a possibility of earlier dates (Lertlum *et al.* 2008; Won-In 2011; Venunan 2011; Yoopom 2010). This pilot study left many open questions and lines of inquiry to be explored, but it began to highlight the potential of a more in-depth investigation.

The major research aim of this thesis was to better characterise the ironworking technology(ies) in Ban Kruat in a broader cultural landscape. I sought to interrogate the large quantities of metallurgical remains to reveal higher-resolution data that could explain this technology in its broader social contexts. Building on the pilot work (Venunan 2011), this research expanded substantially to cover more sites and larger samples in order to be able to tackle a whole landscape of iron production in Ban Kruat and its wider archaeological contexts. A major concern was the integration of technological knowledge with regional archaeology and history, in order to contribute new perspectives to our understanding of the development of Ban Kruat and lower Northeast Thailand, as well as to pave the way for future comparative studies in the broader region.

To reach the above aims, two principal objectives were established as follows:

- To characterise technical and social aspects of Ban Kruat ironworking technology (*chaîne opératoire*). An archaeometallurgical analytical approach was employed to obtain technical data (see Chapter 5); research design and discussion were informed by concepts from literature concerning the study of technology and craft production (see Chapter 2).

Some technical questions were hoped to be clarified:

- What stages of production can be identified in Ban Kruat?
- What degree of variability can be documented in the Ban Kruat iron technology? To what extent did each iron production workshop (slag deposit) share the same technical tradition?
- Can the choices and constraints that shaped said technologies be identified and explained in terms of geology, thermodynamics and sociocultural choices?
- Can the available metallurgical evidence, including laterite fragments, improve our understanding of laterite smelting in lower Northeast Thailand and mainland Southeast Asia?
- Can technical data tell us how iron production labour was organised?
- To what extent can the technologies observed help differentiate different cultural phases in Ban Kruat?

- To contextualise the reconstructed technology and organisation of production within associated archaeological and historical contexts of lower Northeast Thailand and wider contexts. To this end, a detailed assessment of the broader archaeology and history of Ban Kruat was carried out, seeking to place iron production in a revised archaeological framework for lower Northeast Thailand and the wider region.

In order to achieve the above aims and objectives, it was necessary to carry out an extensive critical review of previous scholarship on the history and archaeology of lower Northeast Thailand, with a particular focus on the socioeconomic characteristics of craft production but looking also at broader political and economic structures (Chapters 3 and 6). This review was necessary because archaeological knowledge specifically of Ban Kruat has been very fragmentary, but also because the environmental and sociocultural history of Ban Kruat cannot be separated from that of the broader lower Northeast Thailand. As such, this review was a significant undertaking, given the scarcity of synthetic works, but it provided an essential chronological framework for the current thesis, in addition to informing hypothetical models for the social organisation of iron production which would be tested by newly generated technical data (Chapter 4). Furthermore, the synthesis of the regional archaeology with a focus on technology is presented as an additional contribution of this thesis that should facilitate future studies.

1.1 Layout of the thesis

This thesis is divided into ten chapters. Following this introduction, the following four chapters (Chapters 2-5) provide the foundations of this research in terms of research areas and interpretative and analytical frameworks. This begins with Chapter 2 discussing the theoretical and interpretative frameworks that guided the research design and underpinned the interpretation of archaeological and technical data. Following an introduction to the key concepts and arguments in this framework, two pivotal spheres needed to be discussed in order to lay equally necessary foundations for the later chapters. Chapter 3 attempts to synthesise a culture history for lower Northeast Thailand, covering environmental and political dimensions but also placing renewed emphasis on craft production and its organisation. Chapter 4 introduces general principles of ironworking in general, as well as previous knowledge about ancient ironworking in Thailand. Chapter 5 describes the field methods and laboratory protocols employed to generate data on the metallurgical remains.

The geographical and archaeological background of Ban Kruat is introduced in Chapter 6. Chapters 7 and 8 are intertwined with the detailed characterisation of the metallurgical materials; the former covers the field evidence and the macroscopic examination of the materials, while the latter further presents the findings obtained from structural and chemical analyses. The final section of chapter 8 concerns the reconstruction and interpretation of Ban Kruat ironmaking technology. Chapter 9 socially contextualises the reconstructed technology within its associated background contexts: it elaborates on what this study means for the archaeology of lower Northeast Thailand, and for ferrous archaeometallurgy in mainland Southeast Asia, in both its technical and social dimensions. The final chapter summarises the main contributions of this study against the initial aims and objectives, and suggests avenues for future research.

Chapter 2 Interpretive frameworks for the study of archaeological technologies

2.1 Introduction

The main aim of the study of ancient technologies concerns not only the reconstruction of production process, such as the stages from ore acquisition to finished objects, but also how society interacted with and organised this production activity (Miller 2007, 4-9). To achieve this, technical information needs to be extracted from the production remains by employing appropriate analytical methods; however, these technical data cannot directly convey anthropological information. Therefore, sound investigative and interpretive frameworks are necessary in order to translate these technical data into socially meaningful narratives (Miller 2007, 13-40).

In this study, the principal aim is to use archaeometallurgical evidence to reveal aspects of past societies in Ban Kruat from the technological perspective. As stated in the previous chapter, the path to realising this research involves the reconstruction of the ironmaking process and understanding the underlying reasons that shaped said technology. From there, the relationships between Ban Kruat society and this production can be elucidated. To pursue research along these lines, commonly employed concepts in the study of ancient technologies and craft production are considered. They include the "social construction of technologies" or "anthropology of technology" (Killick 2004; Pfaffenberger 1992; Martinón-Torres and Killick 2015) and "craft production" (Costin 1991, 2001, 2005). Each concept has different applications to tackle and explain the social issues of ancient metallurgical technologies, which will be discussed in the following section.

2.2 Social construction of technologies: explaining technology anthropologically

The first necessary step is to understand what "technology" means to archaeologists and anthropologists. Technology is a term that is somewhat difficult to define, and its definitions have been revised constantly within different philosophical and historical contexts (Dobres 2000, 47-95). Nonetheless, scholarly understanding of technology has already moved away from what Bryan Pfaffenberger (1992) termed as "the Standard View of Technology". This concept viewed technology as an independent force of material development evolving linearly from simple to complex in response to the fundamental need of humans to increase efficiency in everyday life. Defining technology in this way emphasised the natural and material factors at the expense of presenting humans as passive recipients of technology. Human spheres such as political, social, cultural, and economic systems, appeared to have lesser influence in this vision of technology, or to be totally detached from it (Dobres 2000, 10). Technology was thus narrowly conceived as a non-cultural as a manipulation of materials and energy to manufacture and use of objects according to knowledge.

Technology in anthropological and archaeological contexts is now viewed as a human endeavour that is bound by the mechanical and chemical properties of each material but also has social and cultural requirements (e.g. Dobres 2000, 2010; Dobres and Hoffman 1999; Lemonnier 1992, 2002; Pfaffenberger 1992). This means that the development of ancient technologies was not purely dominated by technical factors, but also human factors (e.g. needs, cultural preferences, values, aesthetics, knowledge limitation, social organisation and beliefs). All of these aspects play a role, or a number of different roles, in shaping technology within broader society. Thus, technical and social-cultural-political-economic factors are often intertwined within the world of "technology", and rendering technology inseparable from culture.

Of course, technology is bound by environment and natural laws, hence some aspects of technical activities tend to have cross-cultural similarities. In metallurgy, this physicochemical realm leads humans to manipulate ore and clay in broadly comparable ways by following the rules of physics (e.g. engineering parameters and temperatures required, properties intrinsic to materials) and arranged in the same sequential stages (e.g. procurement, beneficiation, roasting, smelting, and smithing) to obtain desired objects (see further discussion in Chapter 4). However, human cultures and societies have always been diverse in the ways they interacted or dealt with or perceived the surrounding world. This diversification played an equally important role in determining how technical activities were performed in their social environment (Lemonnier 2002; Pfaffenburger 1992, 1998; Dobres 2000, 2010). The result is that ancient technologies were heterogeneous, following different trajectories over time, not necessarily from simple to complex. The challenge therefore is observing these cultural variations in the archaeological record for technological activities. On this basis, the reconstruction of technological aspects from production remains and objects will help us to understand human behaviour in specific contexts, and how societies and technologies interacted.

A number of conceptual frameworks have been developed which allow us to extract information from metallurgical assemblages and to comprehend technology from the technical and human perspectives. One approach is known as "social construction of technologies" (Killick 2004a; Martinón-Torres and Killick 2015). In actuality, this is a collective term for approaches to archaeological material culture that are used for defining technology and its process and identifying underlying reasons that shaped particular technology and create variation. These concepts include *chaînes opératoires* (Dobres 2000, 153-211; Schlanger 2005), technological style (Letchmann 1977), and technological choices (Lemonnier 1992, 2002; Sillar and Tite 2000).

The concept of *chaînes opératoires* is probably one of the most popular. Developed by mid-20th century French prehistorian Andre Leroi-Gourhan to study lithic assemblages (Schlanger 2005), this approach seeks to reconstruct operational sequences of production from procurement to finished objects. However, this is not a simple identification of the process from the first to last step, but its ultimate aim is to understand the network of physicochemical world, society, and technological system as well as behaviours, strategies, preferences and social factors entailed in each step of operation. This means that to reconstruct the *chaîne opératoire* of a technology, all the available evidence (e.g. archaeological, archaeometric, textual, ethnographic, and experimental) needs to be integrated. These sets of evidence are required to identify all possible factors and actors involved in the process of creating, distributing, using, and disposing of objects. When the *chaîne opératoire* is reconstructed, "strategic moments" may be identified. These are essential components which cannot be altered if a specific result needs to be achieved (Lemonnier 1986, 154-155). These unaltered actions in the operation can represent what known as "social choices" (Lemonnier 1986, 155) or "technological choices" (Lemonnier 2002; Sillar and Tite 2000). This is to distinguish them from common behaviours that are fundamentally required, no matter the social settings, to achieve the same result.

The idea of technological choice places emphasis on the technical variation of technology, as there is usually more than one way to achieve a technical goal (Lemonnier 1992; Sillar and Tite 2000). A particular technological choice will reflect social preferences or decision-making actions in order to meet with certain socioeconomic, political, and cultural needs. Different choices made within different social settings often result in different technical behaviours, and this can be described as technological style within the same production operation (technological variation). There may also the case where a choice is restricted by geological and thermodynamic constraints; these factors appear to force certain behaviours to successfully produce desired objects. Nonetheless, this still conveys a message regarding the adaptation of local artisans to their environment. As sets of choices of technological styles are repeated and transmitted, they give shape to technological traditions that can be perpetuated in particular regions, and change over time in adapting to changing natural and social environments.

As discussed, this interpretative framework allow one to fully examine process and interplay of natural and human constraints in iron production. However, in order for all aspects to be revealed and discussed, a complete sets of remains associated with production and use of object needs to be available for investigation. This is known to be challenging as metal-related archaeological sites rarely yield metallurgical remains representing each stage, including Ban Kruat case. Nonetheless, even when it is not possible or necessary to reconstruct a full *chaînes opératoires*, it is stll useful to consider the behaviour chain engaged at any step of the production sequence, as it is these decisions and actions that will an effect the variability of material culture. Characterising this variability can be the first stop to then make inferences about the behaviour responsible for it and the underlying sociotechnical reasons (Hollenback and Schiffer 2010, 320-321; Hurcombe 2007, 38-43; Schiffer 1972, 1976).

In this present research, this broad framework will guide the data interpretation and discussion about how iron was produced in Ban Kruat and what influences guided these actions. To achieve this, both human and material factors need to be considered (to be discussed in Chapters 3 and 4). It is hoped that some aspects of the *chaîne opératoire* or production sequence of Ban Kruat iron production will be reconstructed, and that influential factors can be identified and explained. A broader exploration of technological variation of iron smelting in mainland Southeast Asia may then be possible. The study of technological variation in iron smelting is a recurring theme in some regions, as epitomised in African ethnoarchaeometallurgical research (Childs 1991; Chirikure 2007; Rehren *et al*. 2007). This approach, however, has not been applied much to the study of iron production in mainland Southeast Asia; while it has already yielded interesting results in the study of copper production (see Pryce 2014 for a review). The present study shall attempt to integrate Ban Kruat technical information into a wider picture in order to identify some patterns and alternative choices and styles present in mainland Southeast Asian iron smelting. Besides this, the study will also attempt to explore variation within laterite smelting practices.

2.3 Craft production: investigating how society organised technological practice

As the *chaîne opératoire* of Ban Kruat iron production is reconstructed, it is necessary to examine how this production system was organised within the socioeconomic context of its host society. This requires a more pragmatic approach. The most well-known models of organisation of production, and their archaeological manifestations, have been formalised by Cathy Lynne Costin (1991, 2001, 2005; see also Clark 1995; Nelson 1991). Similar to the previous concepts, this interpretive framework acknowledges the existence and participation of social components in the formation and organisation of technological systems (Costin 2005). This work primarily emphasises political and socioeconomic aspects of the technology and related themes, including specialisation and social complexity. Her approach to the organisation of production provides a clear terminology for the definition of different types of organisation and related components within; including producers, consumers, and the means and natures of organisation, distribution, and consumption (Costin 2001).

This framework, when is used to its full potential, can reveal a thorough picture of how a society organised production as well as implications for the status and role of production in society. However, archaeological evidence, in many circumstances, can be too fragmentary to securely assign production remains to her categories. Nevertheless, if the interpretation is approached with care, even in light of fragmentary evidence, a satisfactory result can still be achieved (see White and Pigott 1996 for an example for mainland Southeast Asia).

Since the work of Gordon Childe, specialisation and specialists are considered at the core of craft production (Brumfield and Earle 1987; Costin 1991, 2001, 2005; Smith 2004). The nature of specialised production varies according to its social setting. Four main parameters: context, concentration, scale, and intensity are used to characterise craft specialists. Context describes the relationship between the producers and elites in the society. It can range between independent (general consumption) and attached production (i.e. producers produce items for elite consumption) (Costin 2005, 1069; Wailes 1996). Concentration characterises the spatial relationship between producers and consumers, whether producers concentrate in a single workshop or dispersed uniformly throughout the consuming population (Costin 1991, 13-15). Scale addresses the degree of labour investment in the craft activity, whether it is kin-based or labour mobilisation by élites. Lastly, intensity refers to whether artisans are full-time or part-time according to their time commitment to the craft activity (Costin 2005, 1055). When combining these four parameters together with socioeconomic, political, and environmental settings, the types of organisation of specialised production can be categorised (e.g. individual specialisation, nucleated workshops, community specialisation, and retainer workshop) (Costin 1991, 9).

Costin (1991, 2001, 2005) has suggested that to characterise the organisation of craft production it is first important to reconstruct *chaînes opératoires*, and these five aspects can then be considered as proxies to link technology to the proposed organisation of production. They include: standardisation/variation, efficiency/labour investment, control over production, output, and technological complexity (Costin 2005, 1064-1069). In this study, the main focus will be placed on standardisation, efficiency, and control, while other proxies cannot be tackled at the moment due to the scarcity of relevant evidence. Standardisation, is a relative term typically used to refer to homogeneity in products. In the study of production remains, standardisation is often inferred from the study of by-products, which inevitably entails some risks (Humphris et al. 2009). It is presumed that production becomes more standardised when artisans employed a controlled set of tools and materials, fixed and routinised practices; these aspects are often associated to fewer producers and the conservatism of specialists to minimise risks, resulting in reduced variation (Costin 2005, 1065). However, the use of standardisation as a proxy for the existence of specialisation is not without its risks; it is important to discern between standardisation that is driven by intentional control over the action, and that which is related to skill, knowledge transmission, and experience (Costin and Hagstrum 1995, 622). One common way of assessing standardisation quantitatively is through a comparison of the coefficient of variation in the technical data of products or by-products (measurable dimensions or chemical composition) (Costin and Hagstrum 1995; Eerkens 2000; Li *et al*. 2014; Martinón-Torres *et al*. 2014; Stark 1995).

Efficiency and labour investment refer to the time, energy, labour, and raw materials input to the work (Costin 2001). The interpretation of this proxy can be very problematic as this is a relative term and culturally contingent. Each society has its own way to define efficiency in practice depending on contextual social needs. Thus, a cross-comparison between two productions (higher and lower efficiency) can sometimes be controversial. It is possible to compare technical efficiency in terms of quantity of yield per ore unit, for example, but without knowledge of the actual economic and social costs of the various parameters invested it may be risky to make inferences in absolute terms.

Another proxy to be considered is control. This proxy and the study of specialisation as a whole are fundamentally related to the study of social complexity and political economy (Brumfield and Earle 1987; Earle 1997; Hirth 1996; Johnson and Earle 1987, 13-14). It has long been argued that control over craft production was a political strategy exercised by elites in order to accumulate wealth, which in return raised and maintained their higher status within the community or between communities (Earle 1997, 7). The rising social complexity in the late Iron Age of lower Northeast Thailand (100BC-AD500) has led many scholars to posit that elites exercised power to control resources for their own political agenda (O'Reilly 2014; cf. White 1995). Craft control has also been raised as an important issue for local and regional elites in later periods (AD500-1453) (Lustig 2009). This thesis hopes to contribute some elements to this debate on the political economy of lower Northeast Thailand.

In this thesis, an effort will be made to integrate the technical data into the wider environmental, socioeconomic, and political contexts of lower Northeast Thailand, in order to contribute to our understanding of the organisation of production. As a large number of samples was analysed, it may be possible to assess the standardisation of production and make inferences about other dimensions of Ban Kruat smelting practices. As acknowledged in many parts of this thesis, the fragmentary nature of archaeological evidence may not allow conclusive discussion of the organisation of production. Nevertheless, some attempts will be made based on a thorough review of the information available. It is hoped that the models proposed can still be integrated into wider discussion of the social organisation of craft production in central and Northeast Thailand (Geary 2012; Pryce 2008; White and Pigott 1996), and evaluated further when more evidence surfaces.

Chapter 3 Lower Northeast Thailand from prehistory to the imperial Angkorian period (500BC-AD1431): environment, socioeconomic development, and organisation

3.1 Introduction

As argued in Chapter 2, it is proposed that ancient technologies were bound and guided by physicochemical constraints but also by the “human” realm (social-political-economic factors). How a particular technology was selected and shaped depended on its technical accessibility and capability, and the extent to which it met the requirements of the societies. These factors framed what technologies were adopted and how the production was operated and organised (Brumfiel and Earle 1987; Costin 2001; D’Altroy and Earle 1985). Elucidating the environmental, technical, and social setting of production therefore allows one to examine further how production may have been organised, valued, and manipulated by elites as part of their strategies to maintain their political power, and moreover why it had been shaped in such particular ways (Earle 1997; Hirth 1996; Smith 2004).

On this basis, to shed light on the place and role of Ban Kruat iron production in a broader regional historical context, it is essential to look at other technologies. This chapter and the following chapter are dedicated to reviewing the social and technical factors which may have shaped iron production in Ban Kruat, but also other technologies and social practices. The information will be instrumental in hypothesising the organisation of the concerned production, a topic which has rarely been touched upon in mainland Southeast Asian archaeology. The hypotheses constructed (see section 4.3.4) will be later tested against the data generated from Ban Kruat throughout Chapters 7-9.

While more specific technical and social dimensions of iron are presented in the following chapter, this chapter intends to review the wider environmental and political-social-economic backgrounds. As part of the rationale for this review, archaeological knowledge from broader lower Northeast Thailand and its vicinity was sought as stated in Chapter 1. In addition, the knowledge concerned, especially for prehistoric periods, comes primarily from the Upper Mun River Valley (Nakhon Ratchasima) for this is the area currently provides the best prehistoric data in the whole region (Figure 3.2) (see section 3.3.1 and 3.3.2). For later periods (Dvaravati/pre-Angkorian and Angkorian period), more evidence can be drawn from other parts of the region (see section 3.3.3 and 3.3.4). This socioeconomic and political background information will later be discussed in conjunction with the archaeology of Ban Kruat in Chapter 6 in order to explore how it could help improve the fragmented picture of Ban Kruat social development.

Previous research programmes have unveiled various aspects of the pre-industrial societies in this region, particularly the periods concerning this thesis, but no overarching synthesis has been attempted previously. The reviews on political organisation and craft production for each period are used to provide a foundation for hypotheses building. However, more generally, this review is presented as a contribution of this thesis that will hopefully be useful for future work on iron or other technologies in the broader region. The data and their implications are drawn from the study of other non-perishable items, such as pottery, bronze, and stone. While the main focus is placed on the production systems, distribution and consumption are also considered as complementary facets in order to have better understanding of the organisation (Costin 1991, 2001, 2005) for each period concerned.

3.2 Geographic and ecological setting

Lower Northeast Thailand is part of the much larger Khorat Plateau. This uplifted land, covering approximately 150,000km^2, has a saucer shape that declines from the higher western edge to the plain in the east towards the Mekong River. It is bordered by mountain ranges and one river (Figure 3.1). Northeast Thailand is divided geographically by the Phu Phan Mountains into two major basins: northern Sakon Nakhon Basin and much larger southern Khorat Basin, where lower Northeast Thailand is. Each basin is separately drained by their own major rivers which are commonly joined by its tributaries. Based on these large and small river networks, each basin is sub-divided into small environmental areas. Archaeology has demonstrated cultural variants (i.e. pottery styles and mortuary practices) in association with each river basin (Vallibhotama 1997; White 1995). Although the material culture shows different expressions of identities for each basin, they were to some extent linked together via exchange networks. As this chapter will illustrate, Ban Kruat is seen to have a strong cultural connection with the Mun River cultural system.

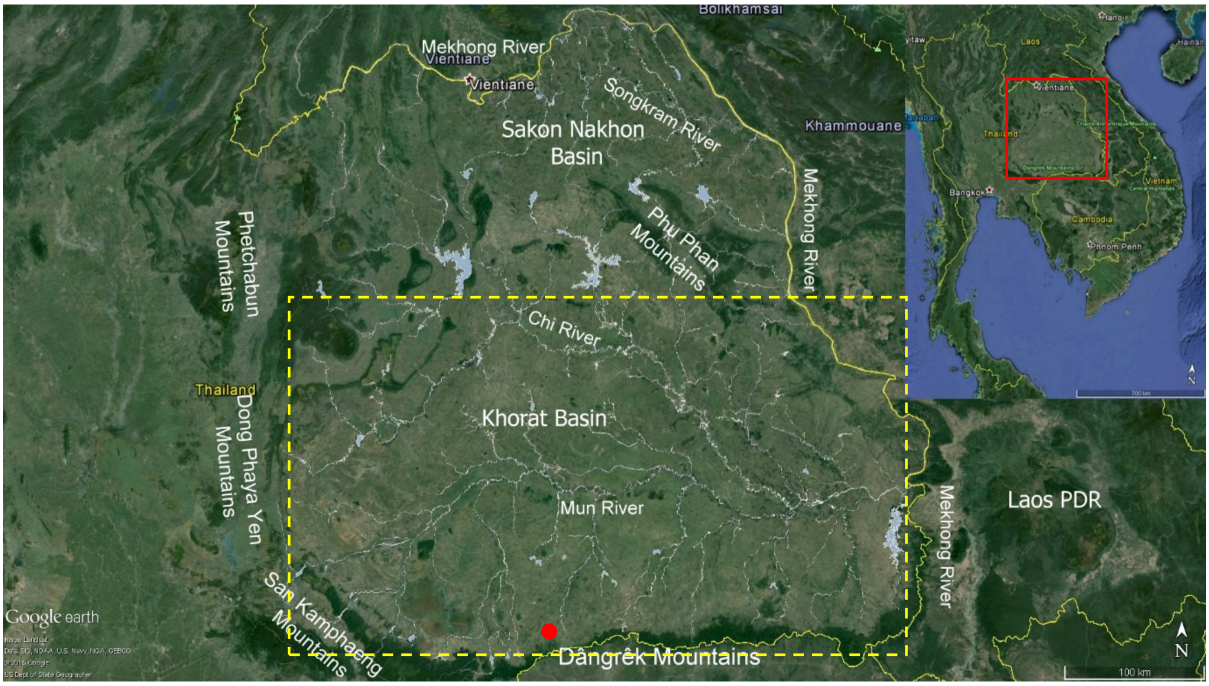


Figure 3.1 Map of Northeast Thailand and its geographical features. Lower Northeast and Ban Kruat are marked by the yellow dashed line and red dot respectively.

Lower Northeast Thailand is drained by two major regional rivers: the Chi and Mun Rivers and their tributaries, flowing eastwards to join the Mekong River. The river networks eased the transportation to Central and northern Northeast Thailand, Laos, Cambodia, and Vietnam. The passes situated along the ranges provide access points into this area. This accessibility allowed the movement of people, goods, and ideas into this region and is a contributing factor for the social changes in this basin.

This study focuses primarily on the Mun River system, to which Ban Kruat is deeply related to environmentally and culturally. This system is a vast land comprising of four provinces: Nakhon Ratchasima, Buriram, Surin, Srisaket, and Ubon Ratchathani located along the *Dângrêk* Range (Figure 3.2). The landscape, heavily influenced by the actions of river system and the geological formation, can be described as floodplain edged by terraces and uplands, sitting upon widely spanned geological deposits of rock salt and laterite.

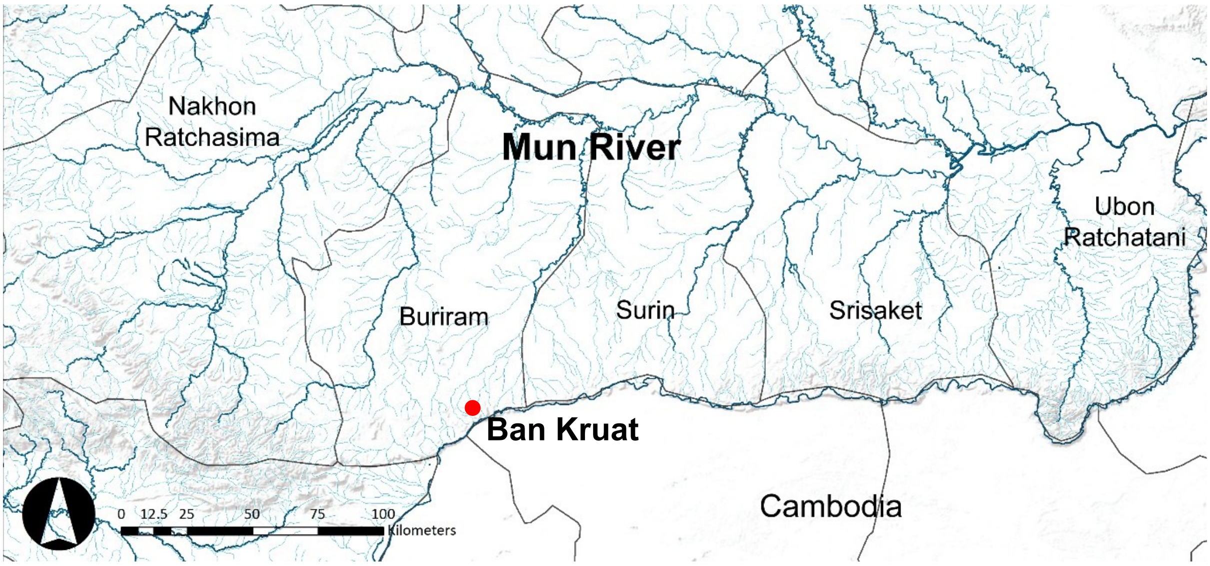


Figure 3.2 The Mun River system and associated provinces.

The floodplain, which was initially better watered by the rivers, was the first area to have been settled as early as the Neolithic (approximately 1800 BC) onwards (Higham 2012; Higham and Kijngam 2010). This zone possessed a superior soil suitable for agriculture and provided various resources, especially foodstuffs, for the occupation. Concordantly to this observation, the highest concentration of settlements were in these alluvial zone along the tributaries of the Mun River (Boyd and Habberfield-Short 2007; Moore 1988; Welch and McNeill 1991). These settlements preferentially occur by rivers or river channels; many of them can be seen nowadays as moated or mounded settlements which are the resultant feature of the Iron Age (Figure 3.3). These mounds are likely to have originally been high grounds before being built up through a continuing occupation and modification that later added moats and embankments in the late Iron Age. The construction of these moats and banks took advantage of their location. River channels and meanders were cut and forced to encircle the sites and, then, using the earth removed to construct embankments, hence, these moats could capture water (Boyd 2007; Boyd and Chang 2010; Boyd and Habberfield-Short 2007; Boyd and McGrath 2001; Boyd *et al.* 1999). Some researchers have argued that this engineering was a response to the need of water during the late Iron Age when the rainfall decreased in contrast to growing communities and increasingly intensified agriculture (Boyd and Chang 2010, 280; Vallibhotama 1997, 94, 108; Welch 1983, 66, 1984, 143). The rainfall, on which the agriculture has relied, can rise to 1,400-1,500mm during the rainy season (May-October) in the annual monsoon cycle, but the geology, which consists mainly of sandstone and salt bedrocks, makes the storing capability of water on the surface very poor. This, thus, poses a serious problem, in particular during the drought season. Thus, these moats could have been utilised as a reservoir as well as a repression of flood or even defence (O’Reilly 1999).

Figure 3.3 Examples of the moated Iron Age settlements in the Upper Mun River Valley

The study of the vegetation history in the floodplains showed that the landscape had been altered since the Neolithic from the original indigenous forest to grassland at the end of the Iron Age suggesting a continuing emphasis on this fertile zone (Boyd and Chang 2010; Boyd and McGrath 2001a, 2001b).

An expansion to settle the terraces and uplands started later, possibly from the late Bronze Age or early Iron Age onwards (Boyd and McGrath 2001a; Moore 1988; Welch and McNeill 1991). The studies in the Phimai area (McNeill and Welch 1997; Welch 1984, 1985; Welch and McNeill 1991) suggested that it was a result of further needs of lands and resources. The terraces were first to be occupied after the floodplain to acquire the agricultural lands. The uplands offered different resources such as game, timber, and iron ore in the form of laterite (Higham 1989, 219). Nonetheless, a critical issue for settlements in this new environment is likely to have been water supply, as the areas were drier, and water conservation was inevitably necessary (Higham 1989, 218, 227-228).

These inhabitable zones remained in focus of inhabitants in the following cultural Dvaravati/pre-Angkorian and Angkorian periods, while there were some changes in settlement plans and hydrological features, particularly during Angkorian period, likely to sustain the further expansion of population and agricultural activities (Figure 3.4) (see section 3.3.4.1.1 for further discussion).

Figure 3.4 Examples of changes in the settlement plans. The left image is an Iron Age moated settlement that a rectangular moat was added to the southern part. The right image is Angkorian temple of Muang Tam which has a diagnostic rectangular baray attached.

Palaeodietary studies have shown that local inhabitants in this region had good access to food, either wild or domesticated/cultivated (Kijngam 2010; King *et al*. 2013; King *et al*. 2014; Higham 2014, 114; McCaw 2007; Thosarat 2007, 2010). Accordingly, the region seems to have been well supportive of inhabitation, since the Prehistory, especially for agriculturalists due to its superiority of soil, and availability of local diet resources. Nonetheless, it has to be noted that, though evidence for agriculture is clear, this activity might have not been equally productive. The fertile lands were likely to have been limited, while others such as terraces and uplands were relatively infertile due to salinity, inadequate availability of water, and laterite.

Besides subsistence resources, there are also other natural resources that supported daily life and industrial activities. They include salt, stone, laterite, and clay. Salt seems to have been a mineral being greatly produced in this region as shown by numerous salt production sites or mounds identified (Nitta 1996, 1997; Rivett and Higham 2007). This resource was probably used widely for food preserving and had been held as a valued commodity from Prehistory to the Angkorian period. It is thought to have been exported to neighbouring Central Thailand or across the *Dângrêk* Range to Cambodia (Hendrickson 2010; Higham et al. 2007, 605; Rivett and Higham 2007). Sandstone and laterite were exploited intensively by the Khmers after the 10th century AD as building materials for constructing Angkorian temples and related buildings (Thamrungruang 2005, 49; Uchida *et al*. 2010). The petrographic and chemical study of stone groups in Northeast Thailand in association with Angkorian constructions found that the builders are likely to have selected suitable stone outcrops close to the construction sites (Uchida *et al.* 2010). The laterite, which is ubiquitous in Northeast Thailand, was undoubtedly exploited during the Angkorian period just as the sandstone. It is likely that the majority of activities involving the use of stones and laterite are associated with the Angkorian period; however, the prehistoric population might also have exploited them, especially laterite for iron production, as demonstrated in this thesis. Clay is also a material that must have been heavily exploited, especially for ceramic production. One notable example is the Khmer ceramic production districts in lower Northeast Thailand, known as the *Dângrêk* kiln group (Chandavij and Chandavij 1989; Prommanoj 1989; Rooney and Smithies 1995; Thammapreechakorn 2009). It should be noted that the term "Khmer ceramic" refers to the ceramics, mainly stoneware, widely produced in the Khmer Empire. The largest cluster of kilns is in Ban Kruat. The Khmers recognised that the high refractoriness of the clay from the *Dângrêk* region, particularly from Buriram, Surin, Srisaket, made it suitable for their stoneware ceramic. This quality was suggested by the refiring experiments of the *Dângrêk* ceramic samples, which suggested that they could survive temperatures of 1,300-1,500°C (Thammapreechakorn 2009, 169-170).

Another equally important resource concerns metals. Archaeologically, copper, bronze, and iron artefacts are amongst common archaeological finds. Despite an abundance of metal artefacts, however, there is one fundamental problem in that major ore sources seem to have been very limited within Northeast Thailand, unlikely to suffice to meet the local consumption. Modern mineral surveys suggest that ores are very scarce and only available in certain areas (Economic Geology Section 2000; United Nations 2001; Yeamniyom 1982); however, small local deposits that are not reported must not be ignored.

Copper ore sources are primarily available only along the Phetchabun-Leoi Fault, where the prehistoric mine of Phu Lon in Nong Khai is located (Bronson 1992, Natapintu 1988; Pryce 2011). Other sources have to be sought outside the region into nearby areas, for instance, the Khao Wong Prachan Valley in the Central Thailand and Xepon in Laos. Both locations have been shown to have been exploited, with their products and distributed regionally and interregionally in the pre-industrial period, in particular the Iron Age (Pryce 2011, 2014). Less widely-known local copper ore sources include Ban Bo Thong, Pak Chong District and Chan Tuk, Si Kew District in Nakhon Ratchasima

(Kanchanakom 1995, 125-126). Tin and lead ores are unquestionably absent. Both metals and their ores must have had to be imported into the region via existing exchanging routes.

The scarcity of typical ores also applies to iron, the metal of interest of this PhD study. The modern mineral map shows very limited iron ore sources with modern economic potential in Northeast Thailand (United Nations 2001; Department of mineral resources 2007). Potential regional ore deposits are only available in the edge of the Plateau such as in Loei which is part of the Phetchabun-Loei Fault (Natapintu 1987 in Kanchanakom 1995, 129). Beyond Northeast Thailand, typical iron ore sources (e.g. haematite, magnetite, and limonite) are ubiquitous, especially in Central Thailand (United Nations 2001; Department of mineral resources 2007) (Figure 3.5). In Cambodia, iron ores are widely dispersed across the country with the highest concentration at Phnom Dek (United Nations 1993) where the remains of ancient iron production activities, likely to have been continued from the Angkorian period to early 19th century AD, were found (Hendrickson 2010, 2012; Pryce *et al.* 2014) (Figure 3.6).

In Northeast Thailand, ancient iron slag mounds and iron artefacts are considered common archaeological finds; while it is likely that many of those iron remains derive from smithing rather than smelting, these statements seem in any case at odds with the fact that only few ore deposits are known. In light of these issues, the hypothesis that iron-containing laterite could have been exploited as an alternative iron ore has been frequently proposed (Chaikunchit 1997, 82; Indrawooth *et al*. 1990, 94-95; Moore 1988; Nitta 1991, 1996, 1997; Welch and McNeill 1991; Venunan 2011; Yoopom 2010, 71) (see Chapter 4). The excavations at the iron production sites in Ban Kruat have provided first-hand evidence for the use of this ore in ancient iron production (see Chapter 6).

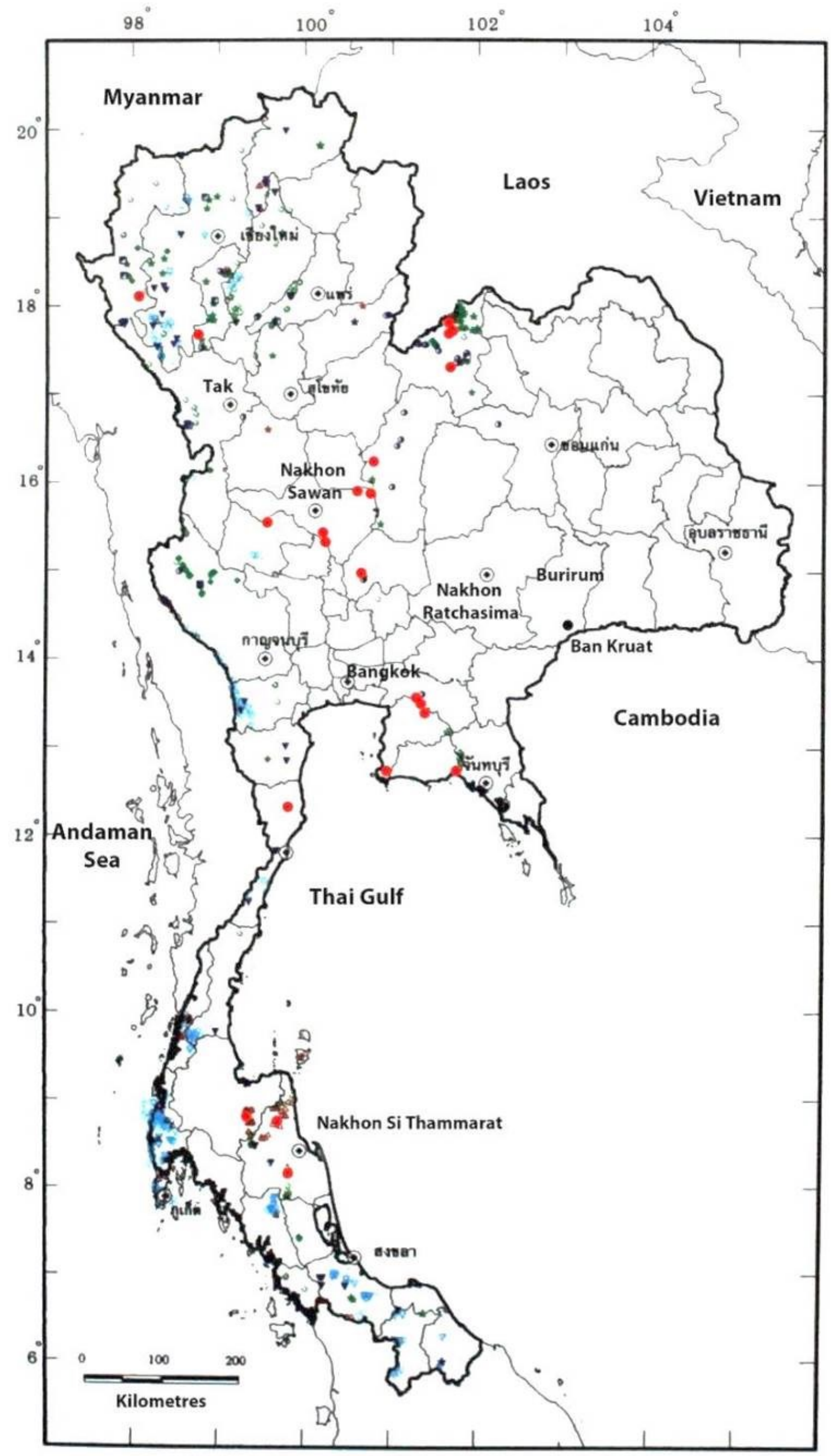


Figure 3.5 Map shows iron ore deposits with modern economic potential in Thailand (red dots). Other symbols represent the sources of other metal ores, not in a focus of this research.
(Adapted from Department of mineral resources 2007, 407)

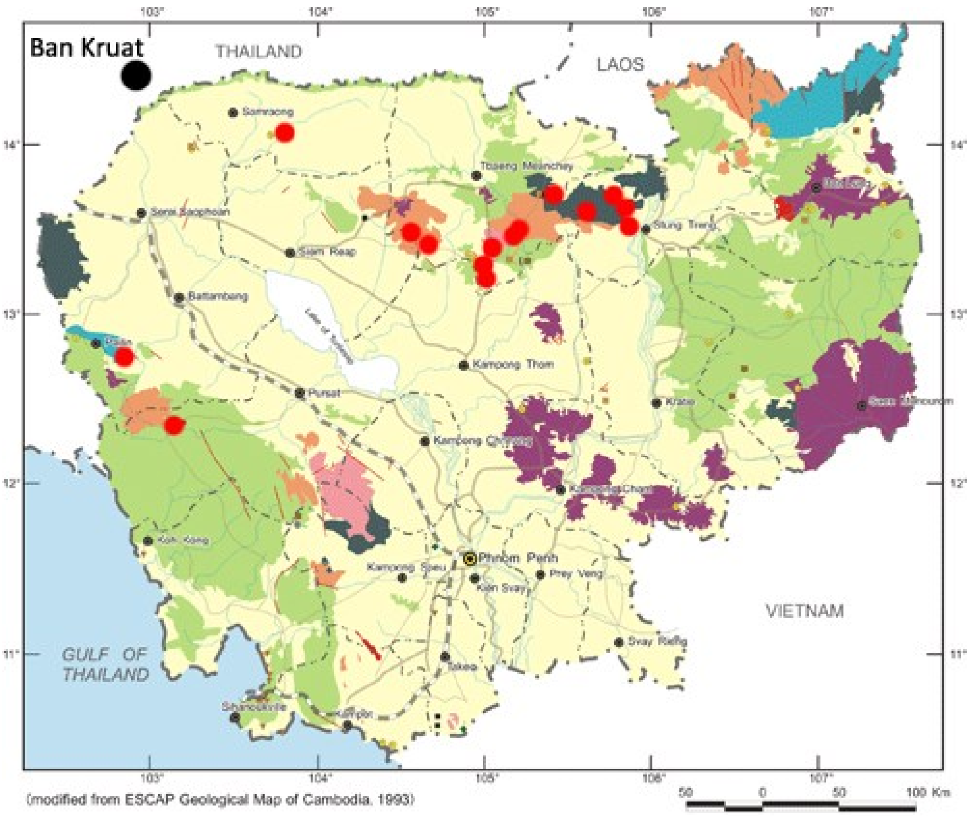


Figure 3.6 Map show iron ore deposits with modern economic potential in Cambodia (red dots)

(Adapted from http://www.gdmr.gov.kh/geology.html)

3.3 Social development in the Mun River Basin

3.3.1 The Neolithic and Bronze Age: a brief overview (early 2nd-1st millennium BC)

It may be informative to provide a brief background for the prehistoric societies prior to the Iron Age (Table 3.1). One of the earliest occupational phases in the Mun River Valley that is confirmed archaeologically is the Neolithic. At Ban Non Wat, this initial occupation occurred in the early second millennium BC coinciding with the migration of settlers that brought with them rice-based agriculture (Castillo 2011; Fuller 2011; Fuller *et al*. 2010, 125; Higham 2004, 46-51; Higham *et al*. 2011b), probable domestication of some animals (Fuller *et al*. 2010, Kijngam 2010; Higham 2004, 46-51, 106; Thosarat 2010), fine pottery, weaving technology, and polished stone tools. This farming settlements are likely to have encountered long-established hunter-gatherers (Kijngam 2010; King *et al*. 2013, 2014; McCaw 2007; Thosarat 2007, 2010). Rice was introduced into mainland Southeast Asia in this phase, but it formed a relatively small component of the diet compared to cattle, pigs, deer, and freshwater animals (Kijngam 2010; King *et al*. 2013, 1685; Thosarat 2010). There was possibly an exchange of marine shell between this community and the coastal sites in eastern Thailand, possibly Khok Phnom Di (Higham and Thosarat 2004, 157). No form of social hierarchy appeared in this period (Higham 2010).

The appearance of the first metal technology known by Southeast Asians marks the beginning of the Bronze Age. Despite a long-running debate over the temporal and spatial origins of bronze technology in mainland Southeast Asia (i.e. Bayard 1971; 1972; Solhiem 1968; Higham 1996, 2011a; Higham *et al.* 2011a; Higham and Douka 2014; Higham *et al.* 2015; Higham and Rispoli 2014; Pigott and Ciarla 2007; Pryce 2014; Pryce *et al.* 2010, 2014; White 2008; White and Hamilton 2009), The dating programmes at Ban Non Wat indicate that the use of copper and bronze in the Mun River Valley started around the first millennium BC (Higham and Higham 2009a, 2009b; Higham *et al.* 2011). This period marked a significant social change as evidenced in mortuary practice. Interregional exchange took place as suggested by the movement of marble, marine shell jewellery, bronze artefacts, and copper ingots (Higham 2011a; Higham and Rispoli 2014; Pryce *et al.* 2014, 291-292). The evidence uncovered at Ban Non Wat raises the possibility, though still unclear and debatable, of early aggrandisers at this site (Higham 2011a, 2011b, 2014, 183-193; Higham and Thosarat 2012, 149); although, for other contemporary sites in Thailand, the evidence appears to have pointed towards the existence of heterarchical societies (Eyre 2011; O'Reilly 1999, 2001, 2003; White 1995; White and Pigott 1996).

Time periods	**Dates**
Neolithic	18th century BC - 11th century BC
Bronze Age	11th century BC - 5th century BC
Iron Age	5th century BC - 6th century AD
Transition into historical period/Early polities (Dvaravati and pre-Angkorian periods)	6th - 10th century AD
Angkorian period	10th - 13th/14th century AD

Table 3.1 Temporal framework for lower Northeast Thailand

3.3.2 Iron Age: increasingly complex societies and interregional exchange (5th century BC-5th century AD)

The Iron Age social sequence in the Mun River Valley has been anchored on the extensive studies at five archaeological sites in the Upper Mun River Valley: Noen U-Loke, Non Muang Kao (Higham *et al*. 2007), Ban Non Wat (Higham and Kijngam 2009, 2010; 2012a, 2012b), and Non Ban Jak (Higham *et al*. 2014). Additional insights are also contributed by other equally essential works in Nakhon Ratchasima (Indrawooth *et al*. 1990; McNeill 1997; McNeill and Welch 1990; Mongkolkhamnuankhet 1991; Wangsook 2000; Welch 1983, 1989, 1998; Welch and McNeill 1989, 1991, 2004) and in Buriram (Archaeology section 2004; Nitta 1991, 1997; Suchitta 1982-1983; Vallibhotama 1997, 2005; Visitchanakun 1999, 26-57) (Figure 3.7). It should be noted that most data have been drawn from the burial contexts, while evidence for domestic life and production of objects is comparatively limited (Higham 2014b, 40).

The Iron Age of lower Northeast Thailand is identifiable by numerous characteristic moated mounds (Moore 1988). More than 227 mounds that have been so far identified in the Mun River Valley (O'Reilly 2014, 303; O'Reilly and Scott 2015) predominate in the landscape alongside the Khmer buildings (Figure 3.8). Some of them are doubtlessly of the Iron Age origin, especially those that are accompanied with characteristic "Phimai black" pottery (Welch 1983, 1984; Welch and McNeil 2004) (Figure 3.9). These pervasive mounds once functioned as habitation sites, workshops, and, most commonly, cemeteries (see section 3.2 for more discussion about these mounds). Studies at these sites have periodised the Iron Age into four sequential phases (Higham 2011b; Higham *et al*. 2012). This began with the advent of iron artefacts around the late fifth century BC (420BC) and possibly ended in the 5th-6th century AD when foreign polities came into contact with the late Iron Age communities. This framework is also applicable for wider regional archaeology considering comparable evidence found at other archaeological sites. Thus, the discussion for this phase will be based on this framework making reference to interregional phenomena when appropriate.

The mortuary offerings of the first phase (IA I: 420-150BC) did not change significantly from the late Bronze Age. The offerings from the preceding period including bronze objects, bivalve shells, and the later Bronze Age pottery vessels filled with foods were continued (Higham and Kijngam *et al.* 2012a). The cultural continuation is suggestive of a stable population. A few sites such as Ban Prasat, Ban Non Wat, and Noen U-Loke appear to be continuously occupied. There were, however, notable changes too. Iron ornaments (e.g. bangles), implements (e.g. spearheads, hoe, and billhook), bimetallic objects, lead objects, and exotic glass, carnelian, and agate jewellery appear in the graves, though, still in small numbers (Higham 2011b; Higham and Kijngam 2012b; Higham *et al*. 2007). Likewise late Bronze Age, evidence for a hierarchical society is still unclear.

Bronze and lead items, as well as glass and semi-precious stone ornaments, reflect both the continuation of previous exchange networks and the emergence of the new ones. Copper, tin, and lead are likely to have been imported through the existing networks (Pryce *et al.* 2011, Pryce *et al.* 2014). This phase saw more bronzes being endowed to the dead (Higham 2011b; 2012b). Furthermore, the exotic ornaments display the involvement of Southeast Asia in exchange with South India (Bellina 2003; Theunissen *et al*. 2000). This movement of items presumably connected lower Northeast Thailand, possibly via Central Thailand, to an entrepôt located in the Upper Thai-Malay Peninsula, with sites, such as Khao Sam Kaeo and Phu Khao Thong (Bellina *et al.* 2014; Bellina and Glover 2004, 73; Bellina-Pryce and Silapanth 2008; Carter 2013, 410), or western coast of lower Myanmar, which traded with South Indian merchants through maritime trading networks. Particularly at Khao Sam Kaeo, this port settlement grew into an urban centre attached with craft workshops that included the manufacturing of glass and hard stone ornaments and iron and bronze objects (Bellina-Pryce and Silapanth 2008, 277-278; Biggs *et al*. 2013; Murillo-Barosso *et al*. 2010; Pryce *et al*. 2006) (Figure 3.10). South Indian and, probably, local craftspeople are presumed to have been patronised by local elites to manufacture beads to meet local tastes (Bellina *et al*. 2014, 75).

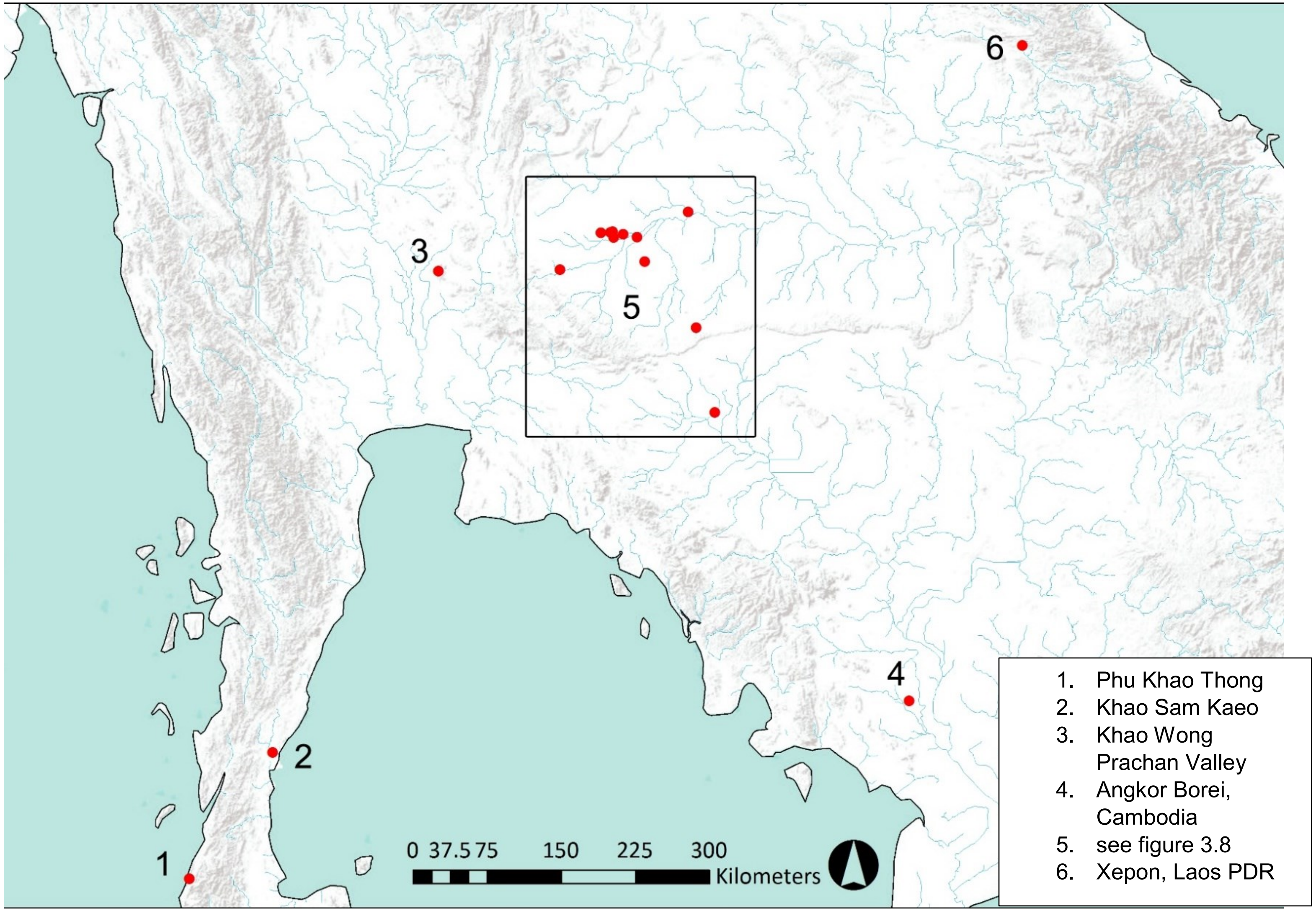


Figure 3.7 Map shows the Iron Age sites cited.

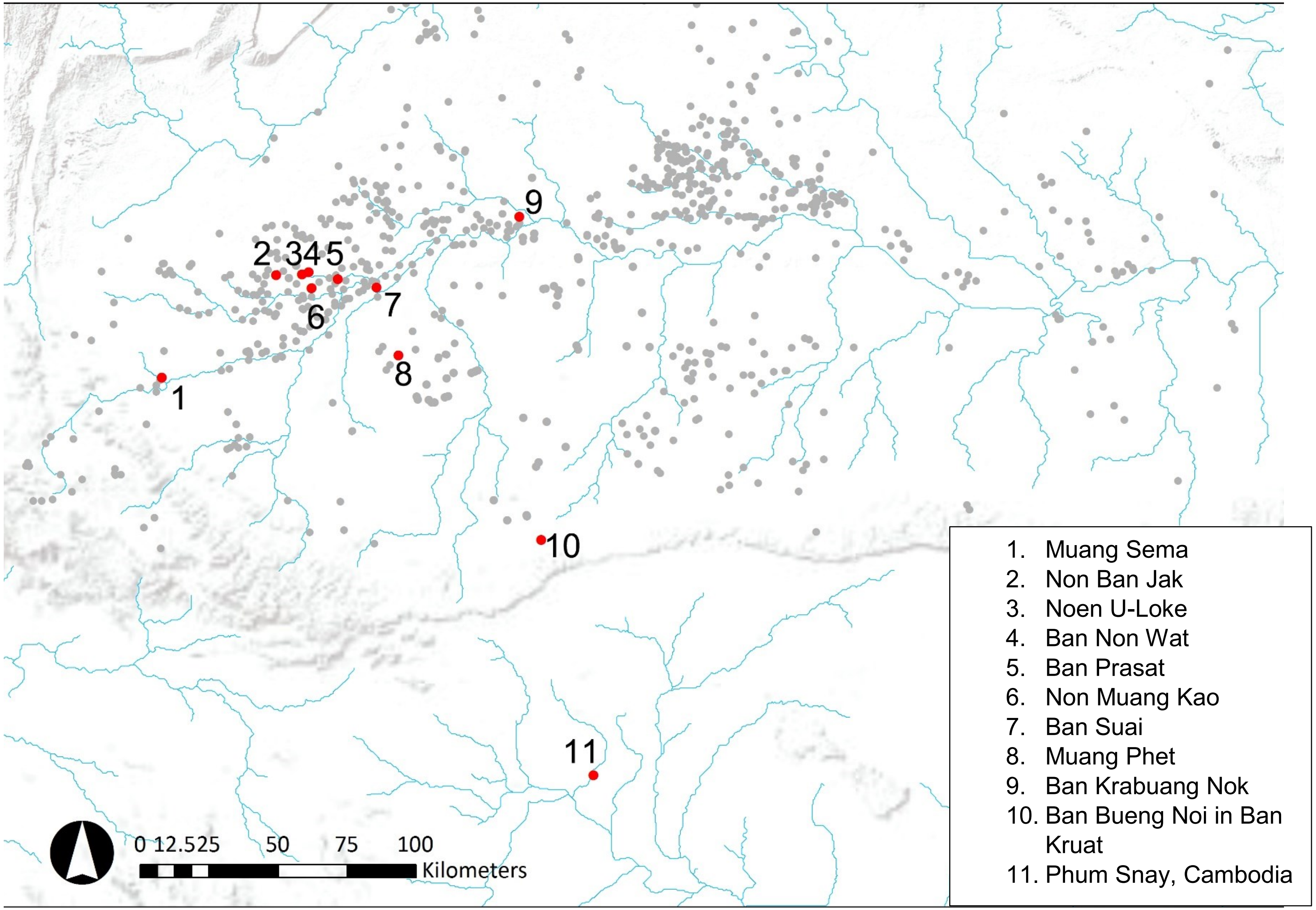


Figure 3.8 The Iron Age sites cited (red dots) among other contemporary sites in the Mun River system.

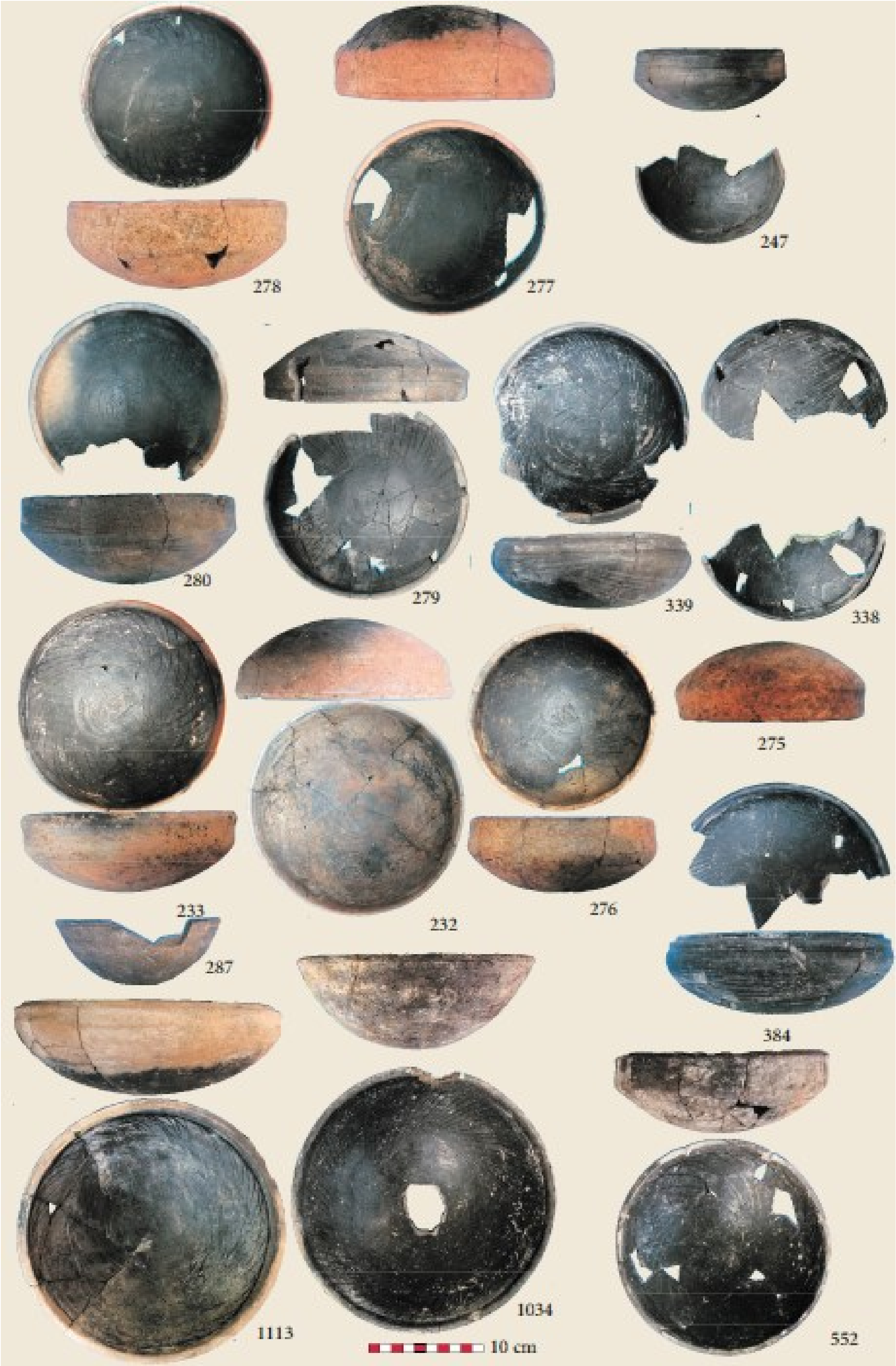


Figure 3.9 Examples of Phimai black pottery from Non Ban Jak

(Image: Higham *et al*. 2014, 35)

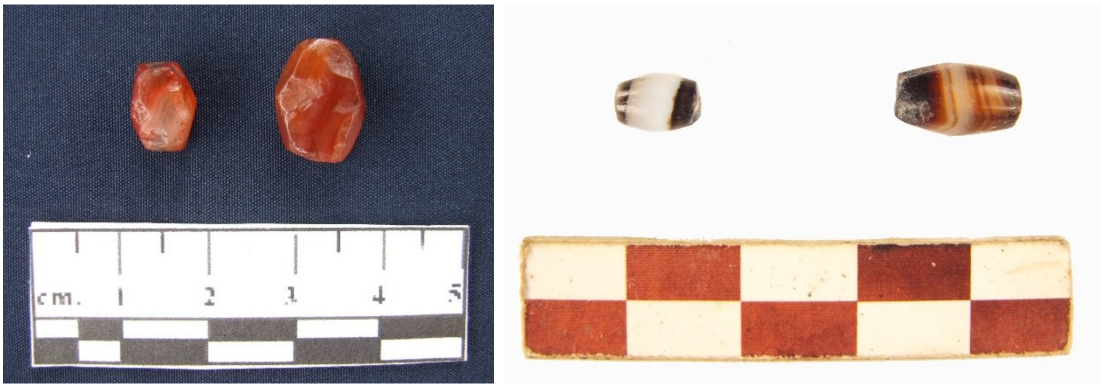


Figure 3.10 Examples of semiprecious stone beads (carnelian (left) and agate (right))

The transition into the second phase (IA II: 100BC-AD200) saw a few critical changes, while most cultural features continued (Higham 2012b, 341). Glass and semi-precious stone ornaments became more accessible to locals. Funerary practices saw changes, such as rice-bed graves (Higham 2012). This may imply that rice, of lesser importance during the late Bronze and early Iron Age (King *et al*. 2014, 117), gradually gained relevance from this phase and was probably produced in surplus. This impression is reinforced by the studies in carbon isotopes of the deceased and palaeoenvironment, which point to an increase in rice consumption (King *et al*. 2013, 2014) and the opening of the floodplains of the Upper Mun River Valley, probably partly caused by the intensification of agriculture (Boyd and McGrath 2001b; Boyd and Chang 2010, 279). Phimai black pottery, which is reckoned as a characteristic Iron Age pottery of this region, probably made its appearance around 200BC as suggested by the works in the Phimai area (Welch and McNeil 1989, 113) (Figure 3.9).

The critical social change took place in the following phase (IA III: AD200-400) which yields better evidence for increasingly hierarchical societies. The tightly nucleated burials containing different ranges and qualities of items illuminate the difference in social status and the wealth of individuals. Rice-bed graves were unrestricted to any sexes or ages, even with infants buried with the same ritual. Some graves were capped or/and lined with clay. Bronze and bimetallic ornaments, iron tools, imported glass and semi-precious stone jewellery (Figure 3.10) were amongst common offerings and in a greater quantity than in the preceding phases. Silver and gold were also used in the ritual of death. Phimai black pottery widely replaced the previous pottery tradition in the Upper Mun River Valley. This ware appears to have been found in many contexts, not only those of ritual activities (Welch 1989, 20). Additionally, the use of bronze appears to have reached its climax as bronze objects increased dramatically during this phase, and some individuals possessed a notable quantity of them (Higham 2011b; Higham and Kijngam 2012b; Higham *et al*. 2007). An increase in copper consumption is coherent with large copper production locales at Khao Wong Prachan Valley and Phu Lon in Thailand and Xepon in Laos which supplied copper ingots for the communities in the Mun River Valley (Pryce 2014; Pryce *et al*. 2011; Pryce *et al.* 2014). In addition to these non-perishable offerings, there is evidence for on-site craft production in the form of industrial remains. These remains encompass the manufacture of various objects, including shell ornaments, pottery, textiles, and metal objects (bronze, iron, and lead) (Higham *et al*. 2007; Higham *et al*. 2012, 16-30).

Rice continued to be a main subsistence resource (King *et al*. 2014, 117) and extensively endowed to the mortuary ritual. Accordingly, rice was likely to have been demanded more than previously. More agricultural iron tools, for instance hoes, sickles, and ploughshares are documented supporting the strategy focusing on agriculture. Clearance of old forests continued in order to support farming (Boyd and Chang 2010, 279). Moreover, this possibly led to the modification of local landscape into moats and banks surrounding mounds in order to sustain water supply for the communities, as discussed in section 3.2. Salt is another subsistence-related industry of importance to locals as a natural preservative. The evidence from Non Tung Pie Pone in Nakhon Ratchasima displays the activity of salt-making during the Iron Age (Nitta 1996, 52, 1997).

Competition over resources may have become a critical issue towards the end of the Iron Age. Newly emerging settlements may be a result of an attempt to exploit more resources, and settlers began to occupy more diverse environments, for instance terraces and uplands (Welch 1984; Welch and McNeill 1991). The initial occupation in Ban Kruat might start in this phase as suggested by the existence of Phimai black pottery, which was found in a burial context (Archaeology Section 2004). There was possibly competition amongst the settlements as some sites in the Upper Mun River Valley are located in close proximity probably creating some stress in the exploitation of resources and land use.

The expansion of communities and increasingly intensified agriculture in contrast to limited water supply might have been a serious problem in the last phase (IA IV: AD400-600). The region was distressed by the decrease of rainfall and a long dry season (Lückge *et al.* 2001; Maher 2008; Wang *et al*. 2005) which affected the productivity of agriculture. As the reliance on rice remained high, the pressure is likely to have been put upon the land owned by each settlements to produce a surplus. A solution may have been the continuation of the construction of water bodies to increase water capacity for agriculture and daily use (Boyd and Chang 2010, 280; Boyd and McGrath 2001b; Higham 2012b). Iron weaponry seems to have been noticeably increased, allowing inferences about the rise of conflict amongst the settlements (Higham 2011b, 139). Despite a solution being made to prolong the occupation, the mortuary evidence suggests a decline in wealth of individuals as nucleated burials faded away.

In these later phases of Southeast Asian prehistory, the maritime trade linked Southeast Asia to China, South India, and the Mediterranean world (Higham 2014; Hung *et al*. 2006; Glover and Bellina 2004; Indrawooth 2004, 2005; Lam Thi 2011; Glover and Yamagata 1998; Theunissen *et al*. 2000; Yamagata *et al*. 2001). The hinterland sites and entrepôts were bound by this activity as exotic goods were imported and distributed to inland settlements, probably in return for goods to be exchanged with foreign merchants. For most settlements, it seems that Indic influences had more social impacts on the rise of early historic polities in Southeast Asia; northern Vietnam is an exception, as it was closely associated with China (Kim 2013; Nguyen *et al*. 2004). Through the exchange, wealth was accumulated by local elites. New concepts which incorporated Hindu and Buddhist religious and political ideologies were introduced and later acted as stimuli for critical social change. This process also involved the incorporation of Indian concepts into indigenous philosophies, and this knowledge may have legitimated or empowered local elites' political rights to compete with others during early centuries AD (Kulke 1986; Wolters 1999, Chapter 1). Archaeology and Chinese texts document the emergence of Funan in the Mekong Delta – one of early states in mainland Southeast Asia – had its roots in the late Iron Age entrepôts. The site of Angkor Borei, thought to be associated with this entity, illustrates a new set of material culture representing Indic influenced ideologies. Brick structures, walls, hydraulic constructions (i.e. reservoirs and canals), inscriptions, and religious artefacts discovered are expressions of new sets of ideas at least partially stimulated by Indic concepts (Stargardt 1986; Stark 2003, 2004, 2006). Funan became a regional dominant power via the control of maritime trade with South India between the 2nd-6th century AD (Stark 2004). Interestingly, available literary evidence shed some light to the people associated with this polity through ethnolinguistic reference. Written in Khmer in addition to Sanskrit, the inscriptions suggest that the majority of people may have been linguistically affiliated with Khmer language. This language is part of Mon-Khmer (Austroasiatic languages) (Bellwood 2004, 11; Blench 2016) that is presumed to have spread to mainland Southeast Asia around 3,000 BC or possibly earlier (Higham 2002, 2004). Arguably, as Funan was likely a cosmopolitan trading port, other languages such as Mon, Cham, and Malay – the latter two languages are in Austronesian language family – may have also been spoken (Vickery 2003). The proposition of ancient Austroasiatic speaking populations in this part of mainland Southeast Asia is debatably supported by the genetic analysis of archaeological human remains from Noen U-Loke and Ban Lum Khao in the Upper Mun River Valley. The samples were linked to the Chao-Bon, a modern Austroasiatic speaking populations living close the sites (Lertlit *et al*. 2008).

Archaeology evidently confirms a constant connection between the Mun River Valley, at least, the Upper Mun River area, and the regions on the southern side of the *Dângrêk* Range which had been established since the Iron Age or probably earlier. Archaeological finds discovered at Phum Snay in Northwest Cambodia have affirmed this link as evidenced in comparable Phimai black vessels, iron implements, imported exotic ornaments (Miyatsuka and Yasuda 2013; Nojima 2013; O'Reilly *et al*. 2006). Evidence for physical violence and conflict is more visible at this site (Domett *et al.* 2011). This connection is likely to have been based on exchange as suggested by the analyses of glass beads and bronze artefacts. Based on the analysis of glass beads, Carter (2013, 2015) and Carter and Lankton (2012) indicated that, in the early first millennium AD, the trade of glass beads in the Upper Mun River Valley shifted from the eastern route to the southern networks which passed Phum Snay to the Mekong Delta, where Funan was located. The relationship between the Mun River Valley and the communities in Cambodia is also supported by the lead isotope analysis of bronze artefacts at Phum Snay (Hirao and Ro 2013), which pointed to the sources of lead in western Thailand as well as southern China. Ban Non Wat might have also acquired lead through these networks, but further examination of Ban Non Wat objects is necessary.

Through this interaction, Indic ideas that sparked the development of early state of Funan may have also penetrated into the hinterlands, including the later Iron Age Mun River Valley, but archaeological evidence does not show a strong interrelation beyond the exchange activity as evidenced in exotic glass beads. It seems that Northeast Thailand might have either chosen not to adopt Indic elements at this stage or been shielded from Indic influence, unlike entrepôts; it was not until the 6th century AD that the Mun River Valley started to witness the rise of early historic polities.

3.3.2.1 Socioeconomic organisation in Iron Age lower Northeast Thailand

Current archaeological evidence for the Iron Age in this part of Thailand collectively indicates significant alterations of the societies and their economies. They have been described to have shifted from arguable heterarchical (O'Reilly 2003a; White 1995) into hierarchical societies which centred on wealth accumulation through different strategies (Higham 2011b; O'Reilly 2001, 2003a, 2014; Stark 2001).

Social inequality and the emergence of elites are apparently displayed by the mortuary contexts in IA III (AD200-400). Some graves were interred with impressive items, either imported or locally manufactured, compared to others. These rich graves in some cases appear to be in tight clusters separating from those considered poorer (Higham 2011b). Bronze items proliferated and, occasionally, an impressive quantity was used to furnish some rich deceased (Higham 2011b, 138). A concentration of wealth to particular individuals indicates a division in social statuses and ranks and the likely existence of elite individuals.

The development of social complexity is also seen in other archaeological features from this period. The construction of channels and embankments, land clearance, and the agricultural intensification required a more intensive system in order to increase labour efforts to perform the tasks. These activities were possibly in response to the growth of population and increase of demand for more resources. Welch (1984, 1989) further proposed, based on the site size and catchment areas in the Phimai region of the Upper Mun River Valley, that there might have been political or economic centres within clusters of settlements. These centres were probably a focal exchange point for nearby settlements that possibly had accesses to different resources. Minor settlements might have supplied the necessary subsistence resources to these centres which might have been unable to produce enough units for their own population.

According to the evidence aforementioned, societies became more complex, at least in terms of labour organisation and settlement status (White 1995, 112). Solutions to cope with the increased unpredictability in resource exploitation caused by rainfall variability, which proved problematic for agrarian-based economy and an increase of population, may have enabled individuals to rise and entrench their power. The elites might have seen an opportunity in solving this long-standing problem by constructing water conservation systems. Elites were able to attract the population to construct this structure. As a consequence of this solution, it enabled elites to subsequently control the water contained and possibly allowed to access to surplus created as water supply became sufficiently available (O'Reilly 2014).

Control over exchange and productions may be other motivating factors stimulating the rise of elites (Carter 2013; Higham 1989, 233-238, 1998, 258, 2014; O'Reilly 1999, 2001, 2014). The Iron Age saw the economy become more dependent on the rice agriculture which was complemented by domestication, craft production and long-distance exchange of luxury goods. Exchange became one of the most intense economic activities. Inferences from habitation sites and graves show that exchange networks were expansive and stretched as far as China and India. Control of prestige goods by elites would have been a way to generate wealth (Brumfiel and Earle 1987, 3-4), probably by controlling over the exchange routes, if the locations of the settlements permitted, or restricting accesses to specific items. Control of exchange became possibly interwoven with a control over the production and products of certain non-perishable goods, such as copper, tin, and lead. The proliferation of bronze objects means that the raw materials were needed, and lower Northeast Thailand seems geologically metal-poor. External sources must have served local demand. The local elites of the settlements along the trading routes where these goods flowed could have benefitted from them and used the wealth generated to exchange for other desired commodities. This might have also been the case for those who also gained rights over the primary production of raw materials (Pryce *et al*. 2010, 258-259).

All in all, this elite class is best viewed as a decision-making authoritative group who could provide suitable solutions to the problems faced (Welch 1984, 130). As the economy was closely linked to the intensification of rain-fed rice agriculture, the challenging environment of lower Northeast Thailand played a major role promoting the establishment of emergent elites and hierarchical structure. Moreover, elites also sought opportunities to ensure their personal wealth in order to create and maintain a high status in their communities. The competition between settlements was possibly an issue caused by resource unpredictability and acquisition. Nevertheless, although control over resources may have generated wealth for elites allowing them to pursue political power, this control was possibly not absolute in that all items were restricted to any individual settlement. Societies, therefore, may have not been centralised or unified, but rather networks of settlements cooperating and/or competing each other. Power possessed by elites was flexible depending on their prowess in solving problems and possibly limited to particular boundary (White 1995). To what extent evidence concerning craft production could support this observation will be discussed in the following section.

3.3.2.2 Craft production in Iron Age lower Northeast Thailand

The Iron Age clearly saw a surge in the consumption of craft objects, especially metal objects and glass and semiprecious stone ornaments. Evidence for regionalised production activity, specialisation, shared space between habitation and industrial activities, and production sites focusing on a particular material is seen in industrial remains.

Ceramic production appears to have been regionalised as suggested by the studies of Phimai black pottery, a diagnostic of the Iron Age sites in this part of Northeast Thailand. These regional wares are found fairly standardised in terms of their recipe (i.e. chaff temper) and formal characteristics (Geary 2012; Welch 1989, 20; Welch and McNeil 2004, 528-529). On this basis, many scholars have suggested the possibility of a regional ceramic tradition and centralised production centres (McNeill and Welch 1990, 331-332; O'Reilly 2001, 11; 2008, 385; Welch and McNeill 1990, 119-120). This may be supported by the restriction of tools for manufacturing pottery at some sites. Notable finds include kiln structures at Non Ban Jak (Higham *et al.* 2014) and Ban Krabuang Nok (Indrawooth *et al*. 1990) and burnishing stones and anvils at Muang Sema (Wangsook 2000, 184), Ban Non Wat (Higham *et al.* 2012, 27), Ban Suai (Talbot 2002; Voelker 2002), and Noen U-Loke (O'Reilly 2001, 11). Considering the wide distribution of this ware across lower Northeast Thailand, the pottery was possibly circulated from specialised workshops via exchange networks (O'Reilly 2001, 11; Welch 1984, 147, 1989, 20; Welch and McNeill 1990, 159, 1991, 332, 2004, 540). A recent chemical analysis of pottery samples by Geary (2012) seems to support this earlier hypothesis. The pottery samples from Ban Non Wat, Ban Suai, and Noen U-Loke inferred that they were produced utilising locally available clays supporting the idea of multiple local ceramic production. Nevertheless, the production is likely to have been strict to particular settlements (Geary 2012, 73; McNeill and Welch 1990, 331-332).

A similar situation applies to copper/bronze production. Exhaustive research on these metals by Pryce (2012, 2014; Pryce *et al*. 2014) has suggested that the mining and smelting activities were confined to very specific areas where the ores concentrated. The archaeological evidence at Phu Lon, Khao Wong Prachan Valley, and Xepon (Figure 3.7) suggests that the activities were intensified, probably as a response to the increase in demand. Arguably, these activities required a set of specialised knowledge and labour organisation. Raw materials (i.e. copper, tin, and lead) were imported into the region, probably via the exchange networks (Pryce 2014, 5; Pryce *et al*. 2014, 290). In contrast, manufacturing wastes for the casting of objects (i.e. crucibles) are indicative of production activities taken place at the household level (Higham *et al.* 2012; Indrawooth *et al*. 1990, 91; Mongkolkhamnuankhet 1991, 40). Pryce *et al*. (2014) proposed that the metals seem to have been circulated and recycled within the region. As proposed for what seen in ceramic production, bronze artefacts might have been produced at some sites and acquired by the consumers who could not produce by themselves.

Other crafts being worth mentioning include cloth and salt. The presence of spindle whorls at most Iron Age settlements indicates that textile production probably took place within the settlements rather than the items being imported. Salt-making seems to have been done exclusively at salt mounds by processing the underground saline water (Nitta 1996, 1997; Rivett and Higham 2007).

As archaeological evidence for industrial activities is sparse compared to mortuary practices, the arguments for craft production have to be constructed cautiously upon few examples of craft production activities. While textile production was possibly a common activity at many settlements, the salt-making, copper-based object casting, and Phimai black pottery production were activities only participated by particular settlements. This might allow these kind of settlements to exchange with or circulate goods to other settlements (O'Reilly 2001, 11) and become specialised production workshops. Phimai black pottery production to some extent might have independently operated in that each workshop accessed independent clay source, but, at the same time, the regional ceramic tradition (i.e. paste recipe and stylistic attributes) was adopted. A wide distribution of Iron Age material culture (i.e. imported exotic ornaments, metal objects, and Phimai black pottery) across settlements, including those which did not participate in non-perishable craft production, suggests that most settlements were able to access exchange networks. This means regional economy was flexible and was possibly articulated around multiple centres (White and Pigott 1996, 168) and may have created a difficulty for elites to tightly control over the production and distribution of these products. This unlikely allowed local elites to accumulate power through a control over the production. On the other hand, if the production could still have generated wealth for elites, what generated is very likely to have been very limited (White and Pigott 1996).

A presence of specialists has also been proposed as suggested by the standardisation in the ceramic production and proliferation of bronze artefacts. This may indicate that the specialists who possessed certain skills and knowledge could have worked, potentially full-time, to meet the demands from the societies. There is also possibility that specialists might have moved from settlement to settlement where they produced objects of desire

(Higham and Rispoli 2014, 22). This might create a shared tradition which is seen in Phimai black production.

Evidence available also suggests spatial organisation of workshops. Many archaeological sites, for example Ban Non Jak (Higham *et al.* 2014), Ban Non Wat (Higham *et al*. 2012), and Ban Krabuang Nok (Indrawooth *et al*. 1990), suggest that the settlement and workshop coexisted; although, some production, such as salt-making, was done at separate mounds.

3.3.3 The Mun River Valley before Angkor: Dvaravati and Chenla state (6th-9th century AD)

At the end of the Iron Age, the socio-political structure in the Mun River Valley was favourable for an increase of social status and power of local elites. Labour management and control over production and exchange presumably continued to be the ways in maintaining their political power in order to compete with other elites. The region was widely populated, and well connected with intra- and interregional communities through exchange networks. Conflicts amongst villages are indicative of intense competition during this period. Despite such social developments and participation in interregional exchange, no unified polities appeared in the valley. However, outside the valley, there were two major polities, Dvaravati in Thailand and Chenla in Cambodia. Their rise was stimulated probably by the Indian socio-political agent which would later have had a crucial impact on the transformation of the Mun River Valley (Figure 3.11).

The contact between these foreign polities and the Mun River Valley may come as no surprise since mainland Southeast Asia was still well connected through the pre-existing exchange networks. Archaeology and political histories point to the significant changes in the Mun and Chi River Valleys, stimulated by the newly introduced ideologies and philosophies. It also has to be noted that, by this period, many of the moated Iron Age settlements in Thailand and Cambodia started to be abandoned; even though, some of mounds were continuously occupied, possibly by locals who adopted the new philosophies.

The findings in lower Northeast Thailand depict the region as an interface of two growing civilisations (Brown 1996; Murphy 2010; Vallibhotama 1997, 120-152). In its broad outlines, the Chi River Valley had been strongly dominated by the Theravada Buddhist Dvaravati in contrast to the Mun River Valley where Dvaravati and Khmer culture were co-existed (Vallibhotama 1997, 120-152). It has to be stated here that the term “Khmer” is used here to loosely represent indigenous polities in Cambodia, in particular Chenla and Angkor. The degree of an interaction in the latter valley between two foreign influences and local identities was arguably high. Dvaravati characteristics were refined and mixed with Khmer culture to create local styles (Brown 1996, 19-45; Murphy 2010; Saising *et al*. 2009; Thamrungreung 2010). This phenomena creates a cultural ambiguity for the understanding of the social development in the valley (Brown 1996, 19). Charles Higham, whose works has focused on the Upper Mun River Valley, has given much credit to the Khmer culture as the principal player behind the formation of complex historical polities in this area (Higham 1998, 2011b, 2012, 2014a, 2014b). However, the influence and impact of Dvaravati on this social development cannot be overlooked.

This period directly correlates with the final phase of iron smelting operation known from the excavation at Ban Sai Tho7 (see Chapter 6). In order to assess the extent to which both civilisations may have had an impact on iron production technologies as materialised in lower Northeast Thailand and Ban Kruat, it is essential to first understand their political, social, and economic structure for both.

3.3.3.1 Dvaravati of Central Thailand

Our knowledge of Dvaravati is strongly based on archaeology and art history, compared to the cases of pre-Angkorian and Angkorian polities, where historical texts play a crucial role (Briggs 1951; Hall 1985, 2011; Jacques 1986; Lustig 2009; Vickery 1998). The few known texts concerning Dvaravati include Chinese texts that refer to the polity as *To-lo-po-ti*, the coins found at Dvaravati sites with the text “*sridavaravatisvarapunya”* (the meritorious deeds of the King of Dvaravati), and a single inscription as “*Dvāravatī*” (Beal 1969; Brown 1996, XXIII; Indrawooth 1999, 2004; Wimonkasem and Prapandvidya 1999). Beyond these references, the particular aspects of political, economic, and social structures and organisations have only been ill-defined.

Archaeology and art history are considered more helpful to characterise Dvaravati on the basis of material culture. The constitution of Dvaravati to some extent is largely defined by the observations at the sites in the core area in Central Thailand. Similar material culture was produced based on shared beliefs or cultural traditions as reflected in carinated pottery and *kendi* (jars with spouts), stamped designs, seals, terracotta skin rubbers, clay pellets, saddle querns and, occasionally, brick religious structures and remains of stone Buddhist *Dharmacakra* (wheel of law) (Aussavamas 2010; Gallon 2013; Indrawooth 1985. 1999, 2004; Murphy 2010; Saising 2004). Some of them show a substantial incorporation of the Indian styles, demonstrating a great connection Dvaravati had with South India (Figure 3.12). Nonetheless, while this approach is suitable for the core area, it is more problematic in peripheral areas, such as Northeast Thailand (Murphy 2010; Saising *et al.* 2009; Talbot 2003; Thamrungreung 2010; Vallibhotama 1997. The approach is also questionable due to the localisation of Dvaravati culture in Northeast Thailand and the similarity between some types of Dvaravati material culture and those belong to other Indic-influenced complex polities in mainland Southeast Asia. The inadequacy of radiocarbon to confirm the date of Dvaravati sites is another critical issue (Mudar 1999); although, the situation has significantly improved from the generation of new radiometric dates which has helped revise existing chronology (Barram 2004; Barram and Glover 2008; Gallon 2013, 82-84; Glover 2010; Khunsong 2013).

Accordingly, the political history of Dvaravati is thought to be enigmatic (Brown 1996, 3; O'Reilly 2007, 65). The debate on the definitions, characteristics, and chronologies of Dvaravati varies depending on what evidence being discussed (e.g. Brown 1996; Indrawooth 1985, 1999; Murphy 2010; Gallon 2013; O'Reilly 2007; Saraya 1999; Skilling 2003). Dvaravati is however viewed here as an archaeological culture that emerged in and was concentrated on the Central Plain between the 6th or 7th-11th century AD (Brown 1996; Gallon 2013; Glover 2010; Indrawooth 1999, 2004; Khunsong 2010, 2013; Mudar 1999). The polity was gradually developed from local Iron Age settlements, stimulated by Indic influence (Indrawooth 1999, 2004). Some of these Iron Age settlements, which are mainly distributed along different river systems (Indrawooth 1999; Khunsong 2010a; Pongkasetkan 2009, 20-25), were succeeded by the Dvaravati occupants, and a few settlements grew into prominent urban settlement sites such as U-Thong (Thaiyanonda 2011), the ancient city of Nakhon Pathom (Khunsong 2010a, 2010b, 2013a, 2013b), Ku Bua (The 1st Regional Office of The Thai Fine Arts Department 1998), Sri Thep, and Chansen (Bronson 1976). The culture then spread to other regions of Thailand, including Northeast Thailand (Figure 3.11).

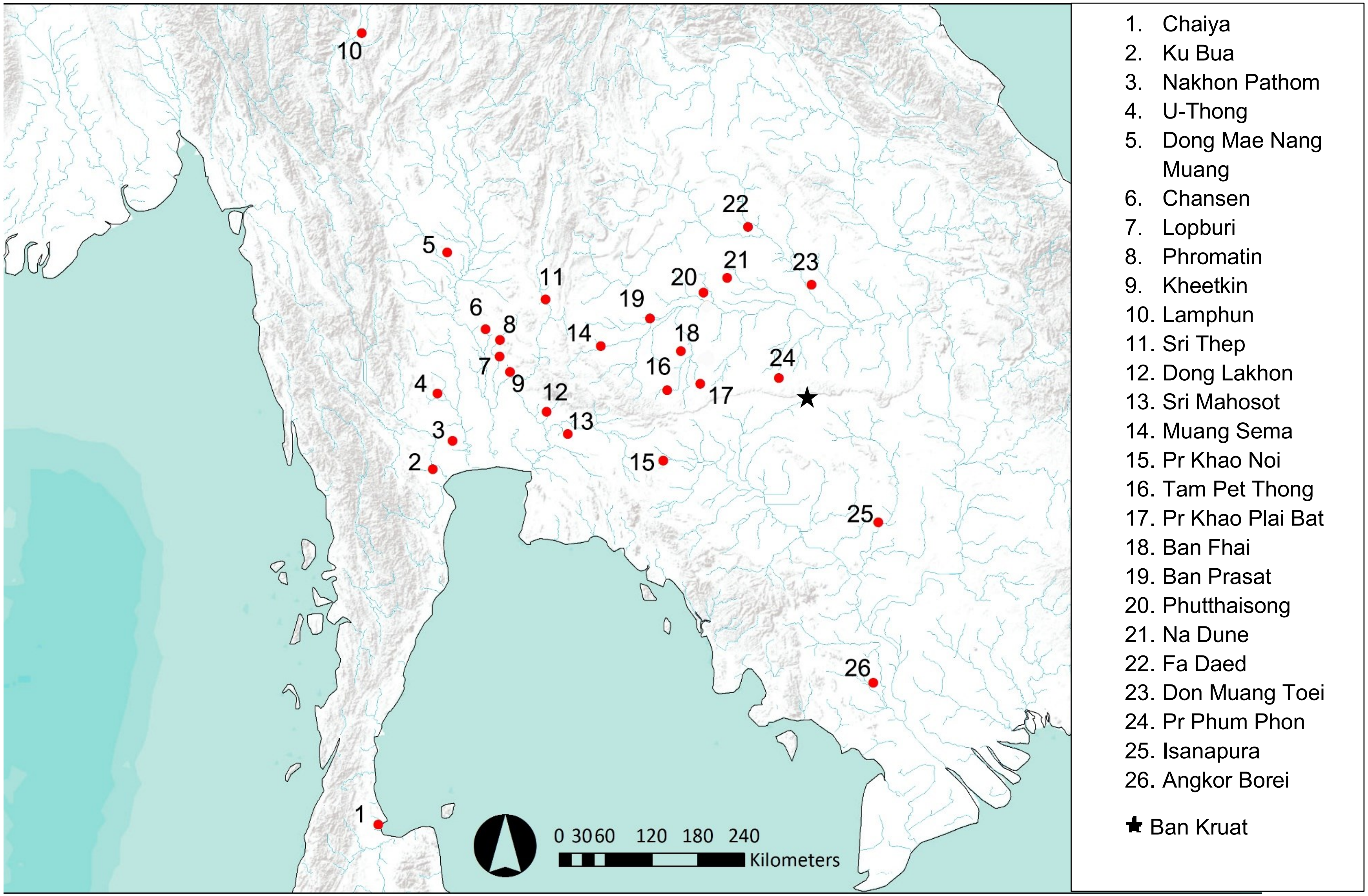


Figure 3.11 Map shows some notable archaeological sites belong to the Dvaravati/pre-Angkorian period.

Figure 3.12 Examples of Dvaravati material culture

(Top row: votive tablet, Buddha statue, stucco in U-Thong National Museum
Bottom row: *Dhammacakra* and architectural remains at Wat Don Yai Hom, Nakhon Pathom)

The Mon population is thought to have been associated with Dvaravati based on the inscriptions; however, this is challenged by the absence of early Buddhist remains in the core of Mon areas in lower Myanmar (Indrawooth 2004, 135). The Mon is a linguistic (Austroasiatic) and ethnic group that is closely associated with lower Myanmar. It may be acceptable to state that Dvaravati was a multi-ethnic polity as its influence stretched to other parts of Thailand, possibly including Khmer in case of lower Northeast Thailand. What is certain is that Buddhism, especially the sect of Theravada, became a dominant religion with other sects of Buddhism and Hinduism also being recognised (Indrawooth 2004, 138). Religious artefacts strongly support this claim, represented by *Dhamacakra* and Buddhist statues.

The least certain aspects as mentioned above are the social and political structures. It is not fully known how the Dvaravati sites related to each other or the level of political integration they had. The political structure of Dvaravati may be illustratively explained by the concept of *maṇḍala* (cf. Mudar 1999). This concept (Wolters 1999, Chapter 2) proposes a cycle of political change inside a group of polities with unfixed geographical boundaries and non-permanent bureaucratic powers over others. Within the political competition, an overlord emerges by gaining a certain degree of power to attract other rulers, and an alliance is formed on this basis. Smaller and less powerful polities may seek a security from larger state(s). This setting can be shifted as the new power arises. In this circumstance, the boundaries of power of each equally powerful state may overlap. On this basis, Dvaravati in Central Thailand might have been a loosely integrated state that shared similar beliefs and material culture. The core centres are thought to have been at U-Thong and the ancient city of Nakhon Pathom for their sizes and exceptional evidence such as various monumental remains, sculptures, and "*sridavaravatisvarapunya*" coins (Indrawooth 2004, 127-130). The society is likely to have been hierarchical consisting of royal family, elites, and non-elites with the king on top of the society. Stuccos display this structure with images of princes, musicians, as well as prisoners (Higham 1989, 279; Indrawooth 2004, 135). Rice agriculture is presumed to have been a main contributor to economy (Mudar 1999, 6).

3.3.3.2 Pre-Angkorian Khmer state of Chenla

The late Iron Age moated communities that stretched from the Upper Mun River Valley to the expanse of the Tonle Sap region shared traits in material culture, especially pottery styles (O'Reilly 2003; O'Reilly *et al.* 2004, 2006; Yasuda 2013). Trade networks connected them to Funan in the Mekong Delta (Carter 2013, 416-417; Vickery 1998, 21). Rice agriculture and water management would have been essential activities together with the trade with coastal sites.

After the 5^{th}-6^{th} century AD, Funan was in decline because of an intense competition with southern maritime trade centres (e.g. entrepôt of the Sunda Strait region) (Hall 1992, 196; Vickery 1994, 6), as well as the heavy resource exploitation. The replacement of elites by the new polity is consistently revealed by epigraphic, documentary, and archaeological evidence. A series of Khmer and Sanskrit language inscribed inscriptions dated to the 6^{th}-8^{th} century AD provides the core information, though they have to be used caution, on certain issues, such as royal lineage, assignments of items, social organisation, and relationship between social classes) (Vickery 1998, 17). Furthermore, the distribution of these inscriptions in Cambodia, Thailand, and Laos indirectly signifies the extension of their expeditions.

The epigraphic evidence details several generations of the royal family of Chenla, whose name was known from the Chinese text. This family progressively attained overlordship over other elites and was able to secure its political authority in the northern part of Cambodia (Vickery 1994, 1998). Its political path became clearer after the appearance of two princes: Bhavavarman and Mahendravarman (the second half of the 6th to the first half of the 7th century AD). The latter prince led an expedition to lower Northeast Thailand; he was probably recognised by locals for he left a series of inscriptions behind (Jacques 1989, 16-17; Vickery 1994, 6, 1998, 74-79). His expansion campaign may reflect the new strategies of Khmers to move away from the deteriorated maritime trade (Hall 1992, 196; Vickery 1994, 6; 1998, 79) and focus on the rice-based economy. This might have encouraged him to explore northwards to secure vast fertile plains. His successor, Isanavarman I (ca. AD612), continued to flourish Chenla. The remains of his city of Isanapura evidence elaborate brick temples, reservoir, and rice fields (Chhum *et al.* 2013; Piphal 2012). Like his predecessors, he attempted to expand his realm beyond Cambodian lowlands. However, his interest shifted to eastern Thailand instead of Northeast Thailand where Chenla inscriptions are absent from this period onwards. Presumably, his presence in the coastal area implies his aim to control a sea exit for the trading purposes, which had still been active (Jacques 1989, 20; Vickery 1994, 11). His intention may be seen in the Khao Noi inscription in Prachinburi which records the local polity of Jyesthapura, administrated by Sivadatta, the son of Isanavarman I (Jacques 1989; Vickery 1998, 347). This polity experienced a short period of independence (Jacques 1989, 18). This evidence suggests that the Chenla political authority might have been weakened and only able to focus on the certain areas (Vickery 1994, 11). While the central power was weak, local polities would have sought autonomy or independence.

Despite the political absence of Khmer in the north of the *Dângrêk* Range after the reign of Mahendravarman, it is still worth mentioning political development of Chenla that possibly had an indirect impact on lower Northeast Thailand. In the 7th century AD, the political centralisation and the territorial boundaries, which covered northern and southern Cambodia, were being strengthened by the reign of Jayavarman I (ca. AD650) (O'Reilly 2007, 117; Wolters 1974, 383). He probably became a supreme overlord during his reign after long campaigns to compete with other principalities that had continued since his predecessors (Wolters 1974, 359, 383). During this early period, Chenla during its early history was presumably a unified polity (Wolters 1974), but its long superiority was only resilient around the capital.

According to Chinese Tang Dynasty annals, some political turmoil subsequently occurred in the 8th century AD in lowland Cambodia. Chenla was split into two large factions: Water Chenla to the south and Land Chenla to the north (Vickery 1998; Wolters 1974). This may have been a result of the competition between local elites for overlordship or autonomy when Chenla lords became weak. It is presumed that Land Chenla might have been politically based around the northern part of Cambodia (Vickery 1994, 16; 1998), though, the middle Mekong Valley has also been proposed (Diskul 1979, 161-162). Lower Northeast Thailand was thought to be part of this entity, as many statelets appear in local epigraphic evidence. Conversely, Water Chenla presumably held southern Cambodia (Wolters 1974, 380). The disintegration continued until the unification efforts by Jayavarman II, who founded the Khmer Empire in AD802, as suggested by the inscription of Sdok Kok Thom (Coe 2003; Jacques and Lafond 2007). In summary, the political history of Chenla was characterised by the struggle of *maṇḍala* polities and an attempt to centralise the power before it collapsed into small polities.

3.3.3.2.1 Social structure and organisation

Chenla inherited some socio-political elements from Funan, such as the all-important hydraulic technology (i.e. reservoirs and canals) and religions, in particular Saivaite cult of Hinduism. While Khmer speaking people is likely to have continued as a dominant population, Chenla society was however more complex and stratified, as suggested by the epigraphic analysis of a series of inscriptions. The social structure was comprised of those who ruled and those who were ruled. For the elites, the king was at the apex known as *vraḥ kamratāñ añ*, the title that was also given to gods (Vickery 1998, 177). The names of kings ended with the Sanskrit –*varman* (i.e. Bhavarman, Mahendravarman, and Isanavarman) (Vickery 1998, 177), a suffix that began to be used in Funan (Vickery 1986, 1998). Below the royalty, there were elites and officials. *Poñ*, also of Funan origin (Vickery 1986, 1998), and *mratāñ* were powerful titles, immediately beneath the king, and both were known as leaders. Then there were ruled classes. *Kñuṃ*, probably translated as slave (see Jacob 1979; Vickery 1986, 1998, 440) is likely to have served as a working class. They were working under the supervision by a chief, possibly known as *kloñ* (Vickery 1998, 275). Free commoners are not explicitly referred to in the inscriptions (Vickery 1998, 226). A class of artisans, including singers, musicians, and dancers is also mentioned by the inscriptions (e.g. K.388) that they are not of *kñuṃ* class, and, occasionally, their names are followed by the high status pronoun (Vickery 1998, 251, 271, 445).

3.3.3.2.2 Political and economic organisation

The inscriptions from this period point to an early form of temple-based economy – the system that would become characteristic of the Khmer Empire. They predominantly refer to the establishment of a god and the founding of a temple by the ruling elites, including king, *poñ*, and *mratāñ.* The inscriptions often include the founders, donors to the temples, and, occasionally, beneficiaries who possibly had rights over the production (Vickery 1998, 275). Offerings listed in the texts range from lands (e.g. ricefields and orchards), personnel, and domestic stock to precious metals (Jacob 1979; Vickery 1998, 274-315).

The personnel referred to in the texts are workers, craftspeople, dancers, as well as other temple functionaries. As part of the donation, they were attached to the temple and assigned to works according to their speciality under the supervision of the chiefs. The lands themselves were probably not under direct rule of kings or higher authority; instead, the inscriptions mention that the owners persuaded by *poñ* or *mratāñ* to surrender their lands for gods, and that they received goods in exchange. Land transactions were likely to be the jurisdiction amongst the owners and higher authority, but the king was rarely involved implying that he did not own the lands. Moreover, *poñ* or *mratāñ* themselves were not the owners of the lands donated. The act of exchange was relied on the barter system rather than applying a medium of exchange such as money (Jacob 1979; Vickery 1998). Various items were used for the exchange of lands including silver, cloth, or paddy (Jacob 1979).

Agriculture was a key economic foundation. The temples, which held the majority of lands, probably managed labours and products. Interestingly, the texts suggest that *poñ* was also closely associated with ponds, fields, and other economic features (i.e. reservoirs, channels, and routes) implying their duty in overseeing agricultural production and supporting infrastructures (Vickery 1986, 97-98, 1998, 190-200, 306). The implication is that irrigation which was important for agriculture and daily life was not subjected to central authorities, but local *poñ* and other chiefs (Vickery 1998, 306). The significance of agriculture is shown by the texts in which rice fields and involved workers are frequently referred. Hypothetically, a large food surplus might have been produced from the lands attached to temples (Vickery 1998, 300-305). Furthermore, a wide range of items mentioned in texts (Jacob 1979) suggests various production activities taken place. Metals, both precious and non-precious (e.g. gold, silver, copper, bronze, and iron), also appear in the texts, but for most activities, no clear reference to the locations or organisations is provided.

Temples were intimately associated with ritual, political, and economic institutions. As the polity was based on a capability to ensure an allegiance of local elites, elites who followed the king were bestowed the rank and legitimacy on local temples. A temple possibly became a property of a clan or family, and the members of the clan were to operate the temple. The temple was also a mean to concentrate and organise resources. The revenues generated within the defined boundaries of lands were channelled to the temple. The permission for the elites to take control over local economy would have strengthened the political alliances. It improved a management and mobilise resources. The size and significance of each temple may be estimated by lands, personnel, and items endowed to them. The surplus probably allowed the civil projects and political campaigns to be continued. The expansionist policies would seek more land and labour for them to increase the yields of products.

3.3.3.3 Early history in the Mun River Valley: an interface between Dvaravati and Khmer polities

As discussed earlier, both Dvaravati and Khmer penetrated into the Mun River Valley simultaneously as early as the 6^{th} century AD. The motivations that brought them to this region seem to have been different, but they jointly and gradually stimulated the transition into the early historic period and introduced the new social and cultural developments that are reflected in the archaeological record. Indic cultural components were introduced through this process of communication with both entities, which saw the adoption of Theravada and Mahayana Buddhism and Hinduism, as reflected in religious objects and architectures. The political ideology was also adopted local elites which stimulated the emergence of the local polities.

Archaeological evidence illuminates the regional interaction between local, Dvaravati, and Khmer traditions, but, at the same time, each major culture (Dvaravati and Khmer) appears to have concentrated on the different areas in this Valley (Vallibhotama 1997, 150-151). The Dvaravati, which came from the west, seems to have extensively influenced the Upper and part of Middle Mun River Valley, particularly Nakhon Ratchasima and part of Buriram. Interestingly, Core Dvaravati tradition was reinterpreted by locals as it settled in Northeast Thailand creating northeastern Dvaravati diagnostic material culture, such as *sema* standing stone depicting Buddhism-related canon (Murphy 2010; Thamrungruang 2010). Many sites in this area yield artefacts associated with Dvaravati, especially the Dvaravati pottery tradition. Some notable sites include Ban Prasat (Mongkolkhamnuankhet 1991), Muang Sema, and Ban Fhai (Visitchanakun

1999, 26-57). These sites were once typical Iron Age moated settlements, but now took on the new tradition. Muang Sema in Nakhon Ratchasima is the most crucial Dvaravati site in this Valley. An imposing 1755m by 1845m two moated enclosure directly correlates with the occupation of the Iron Age and Dvaravati (Hanwong 1991; Indrawooth 2004; Wangsook 2000). Iconic *dhamacakra*, *sema*, Buddha images, monumental remains along with Dvaravati domestic artefacts (i.e. carinated ceramics) were discovered within the site (Thamrungruang 2010, 6-7; Wangsook 2000). Evidence uncovered has made this site hitherto the largest Dvaravati site in the Upper Mun River Valley and is thought to have been a centre of communities.

While the Dvaravati tradition flourished in the western part of the Valley, the social transition in the rest of the Valley (part of Buriram, Surin, Sri Saket, and Ubon Ratchathani) was instead guided more by the Khmer tradition. The movement and impact of Khmers is tracked through a series of inscriptions and architectural remains. The first contact with the Khmers began in the 6th century AD as told by a series of the inscriptions left by Mahendravarman that scatter around the *Dângrêk* Range, mainly in the Mun River Valley (i.e. Nakhon Ratchaisima, Buriram, and Ubon Ratchathani) (Jacques 1989; Musigama 1993; Vickery 1998, 71-81). These 11 inscriptions highlight his campaign to this part of Northeast Thailand, probably to explore potential economic resources, including fertile lands, manpower, salt, and, possibly, iron (Higham 2014b, 822; Vickery 1998, 317). It is likely that locals recognised his political appearance. However, the Khmer influence did prevail but in the forms of material culture, including Mon-Khmer-Sanskrit inscriptions and sculptural and architectural finds.

The events after the visit by Mahendravarman are best described by the 8th century AD inscriptions of Hin Khon (K.388 and K.389) found in Pak Thongchai, Nakhon Ratchasima which mention Nrpendradhipatavarman, who ruled a city of Sro Bra or Sro Vraah, and his donation of meritorious gifts and lands to the local shrine or temple, probably of Buddhist tradition (Jacques 1989, 18; SAC 2010, Hin Khon inscription 1 and 2). K.388 also refers to the regal or noble names: Indravarman and Soryavarman as well as an unknown city of Tamran (Jacques 1989, 18). Poorly studied or dated, but still relevant, altogether the evidence points to the integration of Khmer elements in this region. Prasat Phum Phon is reckoned as the best preserved pre-Angkorian temple in Thailand. This 7th-8th century AD temple may tempt one to link it to the community that adopted Khmer tradition (Thamrungraung 2003, 92-93). It may also be worth considering well-known Angkorian centres in this region, including Phimai, Phnom Rung/Muang Tam, and Phnom Wan. Archaeological works found similar foundation that could be traced back to the Iron Age occupation (Aussavamas 1999; Banthom 2001; Jumprom 2005, 267; Talbot and Janthed 2002).

Beyond the Mun River Valley, a few strands of evidence for Khmer-like elites and kingdoms have been uncovered in the lower part of the Chi River Valley. A name of Jayasinhavarman who ruled an unknown kingdom came to light by the Sanskrit-Khmer inscription K.404 found at Phu Khiao in Chaiyaphum (Jacques 1989, 18; SAC 2010, Phu Khiao inscription). Another kingdom of Sankhapura and the ruler, Pavarasena, is mentioned in the Don Muang Toei inscription (K.1082) found at Ban Song Puay in Yasothon. It tells the erection of linga suggesting that the site once housed a temple dedicated to Lord Shiva (Jacques 1989, 19; SAC 2010, K.1082). The remains of the 7th-8th century AD pre-Angkorian brick temple that was built on top the site of the Iron Age moated settlement confirm the content described (Thamrungraung 2003, 88-90; Vallibhotama 1997, 213-216). Interestingly, the temple was dedicated to Buddhism for a short period as evidenced in the presence of *sema* (Vallibhotama 1997, 215).

The spread of the Dvaravati and Khmer styles to this part of Northeast Thailand gave rise to an artistic hybrid. The Prakhon Chai hoard is one of several illustrative examples; it was found at Khao Plai Bat, approximately 20km north of Ban Kruat. Some of bronze sculptures recovered depict Bodhisattva and Buddha that art historians identified as a mixture of local, Dvaravati, and pre-Angkorian styles (Bunker 1971-1972; Bunker and Latchford 2011, 82; Laomanacharoen 2003). Other example of the artistic conglomeration is further provided by bronze sculptures found at the Iron Age-then-Dvaravati moated sites of Ban Fhai in Buriram (Laomanacharoen 2003; Viriyabhud 1973; Visitchanakun 1999), and Ban Tanod in Nakhon Ratchasima (Laomanacharoen 2003).

3.3.3.3.1 Political, social, and economic organisations

As noted previously, Iron Age societies had developed hierarchies. The social structure was probably governed by elites, whose power was established, consolidated, and maintained through successive controls over economic institutions to various degrees. Rice agriculture, the irrigational construction, the production of materials, and the trade of exotic items were probably central issues for elites (O'Reilly 2014). The continuation of the Iron Age settlements in the Mun River Valley denotes the ability of elites in attracting supporters who became their labour. The success in organising the workforce would have fostered the competition. The complexity of political, social, and economic organisation led Higham to term the society as "proto-*poñ*" (Higham 2012).

Around 5th-6th century AD, many Iron Age moated settlements began to be abandoned, possibly caused by environmental fluctuation. Many surviving settlements may have continued their preceding organisation, while Indian conceptual models, possibly through the contacts with Dvaravati and Khmer polities, was selectively adopted and adapted to indigenous socio-political form. This action is explained as an attempt of local populations or elites to seek out new institution that allowed them to participate in supra-community political competition. Various instances support this social change. New material culture, such as inscriptions, ceramic styles, Buddhist and Hindu-related objects and structures, and rectangular reservoirs was adopted by local populations. Settlements were also expanded and incorporated new site plan (i.e. rectangular plan). It is plausible that elites were able to persuade populations to commit themselves to civic activity programmes. Manpower and labour organisation were required to construct water management structures and monuments and fabrication of religious objects. These factors might have encouraged the merger of various small settlements and relocation of the population to the new and larger settlements in addition to an expansion of some preceding settlements (Higham 2014b, 832).

Current archaeological and epigraphic evidence suggests that contemporary societies in the Mun River Valley were possibly described as a decentralised collection of politically struggling polities or *maṇḍala* (Wolters 1974; Vickery 1998). Some settlements followed the Dvaravati tradition, especially those accompanied with *sema* (Murphy 2010, 150), and some of them were expanded into considerable size (e.g. Muang Sema and Ban Fhai). Many Dvaravati-related sites see Khmer traits merged with Dvaravati culture with exception of Muang Sema that Khmer cultural intervention was very light, at least until the 10th century AD. Contemporary evidence is too scarce for this thesis to suggest the political organisation.

The role of pre-Angkorian Khmer culture in the Valley is comparably clearer as explained by the contemporary inscriptions. The recurring theme in the surviving written records in conjunction with the archaeological findings in this region is the rise and fall of small polities or *maṇḍala,* actively competing each other for supremacy (Wolters 1974; Vickery 1998). Many diplomatic missions to China seeking for acknowledgement and recognition were commissioned (Smith 1979). For the sites where Khmer or Sanskrit inscriptions were discovered, Khmer elements might have been integrated into the political domain of local elites. The rulers bore the Sanskrit divine titles, similar to the Khmer leaders (e.g. –*varman* and –*sena*). This shows, to some extent, an incorporation of Khmer element into indigenous components. The main religious theme, either Hinduism or Buddhism, was worshipped by the rulers, and possibly their followers. Interestingly, religious conversion also occurred as in the case of Ban Song Puay (Don Muang Toei). Temples, inscriptions, the services, and production of religious objects, likely to have been commissioned by the rulers or high-ranked officials, would have served to advertise their increasing power and, probably, to promote the social integrity of the community (Mann 2012, 2-3). This would have eased the mobilisation of labour for the required tasks.

It is not clear the extent to which the pre-Angkorian temples in lower Northeast Thailand would have operated following the same economic mechanism as identified in the Cambodian inscriptions. While the Hin Khon and Don Muang Toei inscriptions respectively report gifts being donated to a Buddhist temple and the erection of linga, it is less clear the extent to which the practice followed an exclusively religious purpose, or it represents a similar pattern to that illuminated by the Cambodian inscriptions. The few remains of pre-Angkorian temples in lower Northeast Thailand may suggest that not all communities adopted this system. Considering political fragmentation in lower Northeast Thailand during this period, the temples might have neither been connected nor centralised but, probably, functioned within their own limited boundaries that each polity could control. This pattern was likely to be changed during the Angkorian period as the network of temples was established to allegedly control the production and goods.

3.3.3.3.2 Craft production in the early historic period

While the regional socio-political development is largely revealed by the contents in the inscriptions complemented by associated material culture, the productions and how they were organised are not the main theme of these texts. Moreover, most studies focusing on this period have not paid much attention to this particular aspect of material culture.

One study on the Dvaravati pottery assemblage from Muang Sema has provided some relevant, albeit limited, evidence (Aussavamas 2010, 2011, 2012). Based on the petrographic study, the author saw a continuity in the use of local raw material tempered with rice chaff, a recipe which had been continued since the Iron Age (see section 3.3.2.2). On this basis, despite the morphological similarities with ceramics in the core area in Central Thailand, the analysis indicated that local potters inherited the technical knowledge and preference from the preceding period, adapting it to new influences. The excavation supported this proposition as a clay paddle with decoration and a possible kiln structure were found (Wangsook 2000, 65, 120); however, more evidence is needed to confirm that ceramic production took place on the site. The tradition which produced pottery locally is also seen at Ban Krabuang Nok where the kiln remains were identified

(Indrawooth *et al*. 1990, 108). Furthermore, it can be inferred from the analysis that lower Northeast Thai Dvaravati rice-chaff tempered pottery were found in Central Thailand further supporting the continuity of exchange between Central and Northeast Thailand (Aussavamas 2010, 2011, 2012).

Further information, though still very limited, concerns the metallurgical craft, with an evidence (i.e. crucible and mould fragments) from Ban Krabuang Nok suggesting a continuity in the activities from the Iron Age at the same site (Indrawooth *et al*. 1990, 56, 91-92).

Little is known, however, about the organisation of labour. Iron Age research posits that labour was apparently organised to engage in the civil constructions, such as channels and embankments. In this period, the brick monumental construction and expansion of the settlement plans probably point to a similar story. These features are strongly indicative that local elites maintained authority over the population which allowed them to mobilise labour for these projects. It is feasible that ritual ideologies might have played a role in increasing labour efforts in addition to the previous environmental factors. Considering a scarcity of current evidence for craft production, the applicability of this model to craft production remains hard to ascertain.

3.3.4 Lower Northeast Thailand in the context of the Khmer Empire (9^{th}-14^{th} century AD)

As it is mentioned previously, the social history in lower Northeast Thailand was significantly conditioned by two main external sources. While the Dvaravati tradition was strong in the Chi River Valley, the Khmer culture deeply settled its root in the Mun River Valley; even though, the Dvaravati-influenced polity at Muang Sema coexisted with the Khmer. The impact they had on this region resulted in the rise and fall of small competing, but fragile, polities or *maṇdala*. This situation changed dramatically when the new Khmer state rose in the 9^{th} century AD. The political entity, later known as the Khmer Empire, would became a dominant state at its apogee between the 11^{th}-12^{th} century AD before facing its demise in the 15^{th} century AD (Figure 3.13). It was during these centuries that lower Northeast Thailand was presumably under a hegemonic banner of Angkor (Vallibhotama 1997, 166-180), the term that is applied to both state and capital. Inscriptions and pervasive imperial Khmer material culture in forms of statuary, architectural, occupational, and production remains continue to be major informative sources shedding light to the political, social, and economic structures (Hall 1985; 2011;

Jacques 1989; Lustig 2009; Sahai 1976, 1977a, 1977b; Sedov 1978). However, it should be noted that the proposed models for the Khmer state organisation are often generalised for the state as a whole, while the peripheral regions lack of detailed studies (Welch 1997, 1998).

3.3.4.1 The Khmer Empire: an overview

The Khmer state may be seen as a developed form of the pre-Angkorian polities; many components were continued, for example the king title and the economic focus, but there were also changes such as the replacement of *poñ* and *mratāñ* with the new titles (see section 3.3.4.2.1) (Vickery 1998, 406, 2004, 4). The state was found in AD802 by Jayavarman II, ruling from c. AD802 to 835 on the northern bank of the Tonle Sap, which would remain the core area until the fall of Angkor in AD1431. This founding of Angkor followed the relocation of his stronghold from the south where he had probably reached an alliance with the polities (Stark 2006, 155; Wolters 1973; Vickery 1998, 393). The motive behind his move to the northwest may have been the willingness to gain an access to a wider variety of resources, which in the long run would place him in a better position, rather than relying almost exclusively on the rice agriculture (Hall 2011, 160; Vickery 1998, 316-317). The local geography, through the extensive water management, also sustainably supplied water for habitation and agriculture at Angkor and its vicinity (Fletcher *et al*. 2008a, 2008b; Kummu 2009). Moreover, this location allowed the Khmers to travel to the further hinterland (Thailand and Laos) where more resources, essentially cultivable lands and labour, were available. As a core area for the empire, all first four capitals (Hariharalaya, Roluo, Yasodharapura/Angkor, and Koh Ker) were located in this area, and numerous Khmer monumental, settlements, and industrial remains have been documented along the banks of this lake with the highest concentration in the Angkor region (Evans *et al*. 2007) (Figure 3.14).

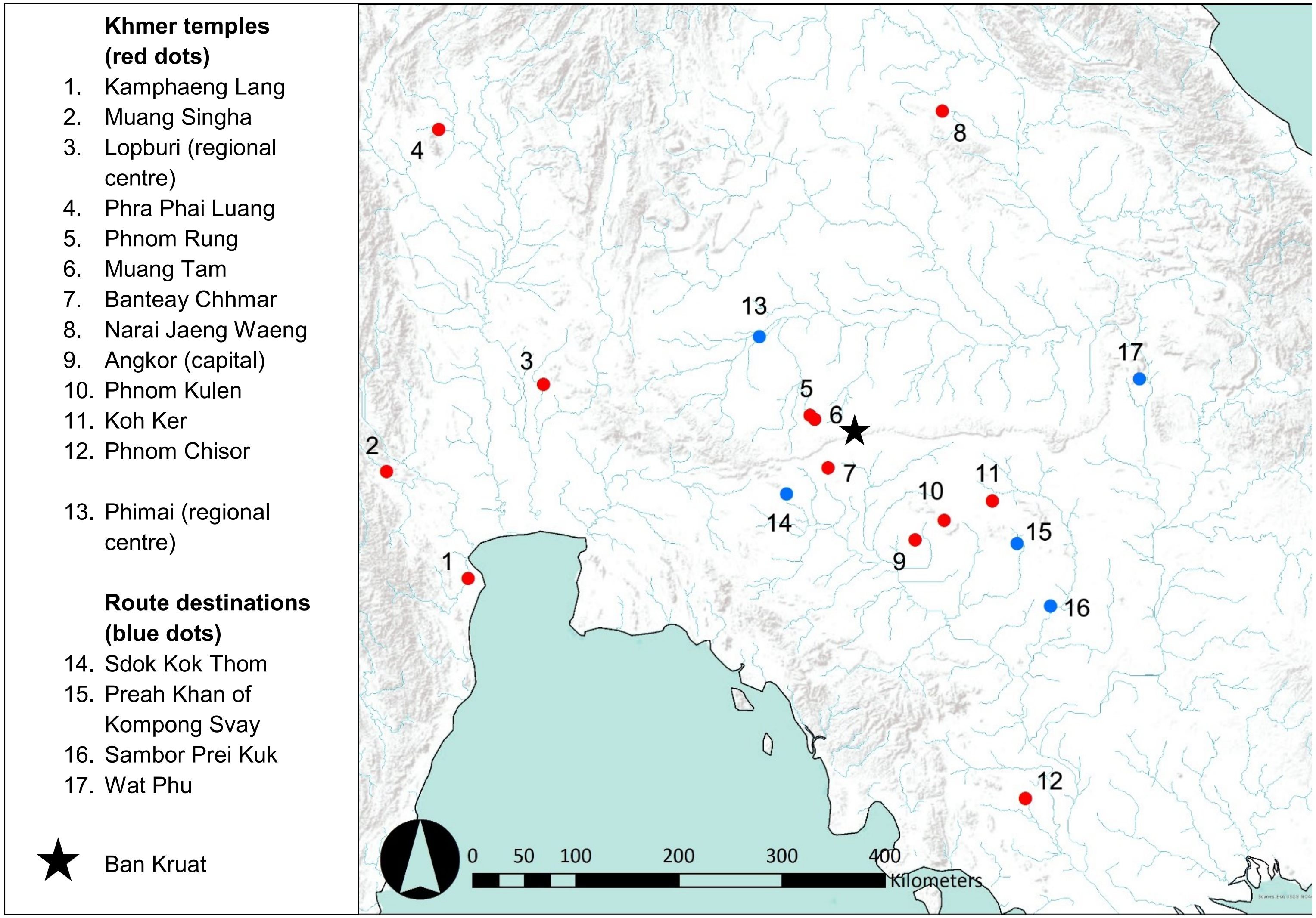


Figure 3.13 Some important Angkorian Khmer temples.

Jayavarman II proposed a newly developed political ideology that was intimately linked with a religious institution, mainly in association with Saivaite Hinduism, symbolically making him a king above all Khmers. The later kings also occasionally incorporated Vaishnavism and Mahayana Buddhism into this cult. This ideology is known as the royal Khmer cult of *kamraten jagat ta raja* (in Khmer) or *devaraja* (in Sanskrit) (god-king). It assimilated the kings to the gods in order to legitimate the kingship and consolidate the king's supremacy over his realm and other competitors (Jacques and Lafond 2007, 103; Kulke 1986, 15; Mabbett 1969, 204; Mabbett and Chandler 1995, 164-165; Wolters 1979, 440-441). Aided by the priests as a medium, the kings, through the symbolic expression, held the divine power in place of the gods (Mabbett 1978). This concept was an additional political tool for integrating the state for it amalgamated other deities or beliefs into the state's religion, collectively worshipping the main deities (Hall 2011, 168-169). The portrayal of the foremost deities (e.g. linga and Vishnu and Buddha images) was installed at the main and subordinate temples that were built across the lands embodying the symbols of the authority (Sedov 1978, 115). This policy enhanced competitiveness of the Angkor's kings by helping unify and merge other members or elites into the unified political system with the king at the apex. This cult effectively complemented other diplomatic and military approaches such as marriage, cooperation, and military coercion with the goal of unification and, later political and cultural expansion (Hall 2011, 168; Lustig 2009; Sedov 1978, 114-117; Wolters 1973). The cult seems to have been a powerful tool in giving an absolute power for the kings, but, in actuality, their political power depends on the capabilities of each individual to administer his realm, and the integration of the state persisted as long as the allegiance prolonged. Wealth distribution and patronage were seen as strategies to ensure the royalty and commitment of local elites or political members to Angkor (Lustig 2009, 227-228). It is likely that loyal members were given privileges such as tax exemptions or wealth from surplus generated from the lands these members controlled.

Even though the king's power was justified by the cult, struggle for the unification continued for centuries, but this political instability contrasted with the growing economy and territorial expansions (Hall 1975, 323-324, 1979, 242; Jacques and Lafond 2007). This progress is reflected in a rising number of public works in the heartland, including the relocation of the capitals and the construction of multiple temples and massive water reservoirs (East baray), which was initiated by Yasovarman I (AD889-910). The urban areas or town/cities (-*pura*) proliferated in the reign of Rajendravarman II (AD944-968) and Jayavarman V (AD968-1001) as a result of the improving economy (Hall 1975, 323-324, 1979, 242). The consolidation of the political power at Angkor came under the reign of Suryavarman I (AD1002-1050). In his reign, there was evidence of the oath of allegiance by *taṃrvāc*, possibly either members of each clan or local elites that were willing to follow Angkor (Lustig 2009, 226; Mabbett and Chandlers 1996, 166; Sedov 1978, 119). This improved political situation in Angkor benefitted Angkor's expansionism which allowed it to strengthen the Khmer rule in Northeast Thailand and later expand his influence to Central Thailand (Hall 1975, 2011, 171-185). This action may have been motivated by an eagerness to participate in maritime commerce and a need for more resources to sustain the developments (Hall 1975, 2011, 177). A stronger authority in the western territory enhanced its agrarian-based economy as more lands and labours, thus resources, were available. Flourished commercial activities are also seen in this period (Hall 1975). The following decade saw a shift in the new dynasty which its origin was possibly related to Northeast Thailand (Suksvasti 1988, 29-30) and the construction of Angkor Wat and the constant wars with Champa. The last peak of the Khmer civilisation took place during the reign of Jayavarman VII (1181-1220). He found the new capital city of Angkor Thom within the Angkor region (Mabbett and Chandlers 1995, 207) and imposed Mahayana Buddhism as a state religion replacing a long tradition of Saivism. Various civil and military actions were commissioned by him to restore order after the constant conflicts. This included wars to supress rebellions and with the kingdom of Champa and attempts to strengthen the centralisation by improving infrastructural systems (e.g. transportation, health care) and installing his royal family members and iconic statuary at the strategic locations across the empire (Figure 3.15). His strategies had his empire stretching from Cambodia to the western part of Thailand (Figure 3.13). Jayavarman VII's death marked the start of a long degeneration period for which the severe environmental change (Evans *et al*. 2007, 14281; Buckley *et al*. 2010), unsustainable economy, and the rise of the new powers in Central Thailand (Vickery 2004) were collectively responsible. It was not until AD1431, however, that the Khmers abandoned Angkor due to the invasions by the kingdom of Ayutthaya (Briggs 1948).

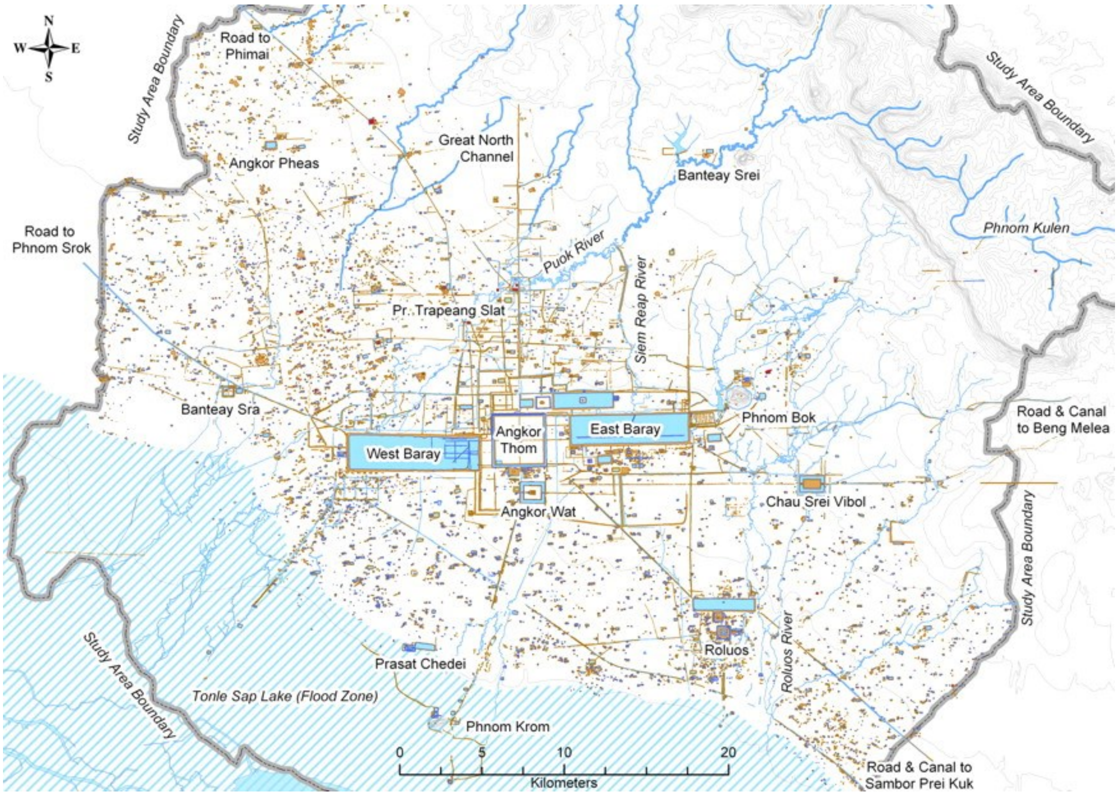


Figure 3.14 Map shows the Angkor region, the political core of the empire

(Image: Evans *et al*. 2007, 14280)

Figure 3.15 Map of the Khmer route system.

(Image: Hendrickson 2010, 482)

3.3.4.1.1 Lower Northeast Thailand: a western territory of Angkor

The previous section discussed broadly the historical course of the Khmer polity in which lower Northeast Thailand was politically assimilated. This section addresses in more detail how lower Northeast Thailand progressed during the rise of the Khmer empire (Figure 3.16).

To Khmers, the trans-*Dângrêk* Range was a familiar well-populated region. Its diverse environment had much to contribute to the growing economy of Angkor. Fertile floodplains of the Mun and Chi River Valleys could facilitate the Khmer agrarian-based economy. Furthermore, Angkor could have also benefitted the industries of salt and iron and the connecting routes to Central Thailand and western coastal regions.

During the formative phase of Angkor, the situation in lower Northeast Thailand had not changed considerably. Local elites were still loyal to their own sovereign. An autonomous kingdom of Sri Canasa or Canasapura is referred to by two inscriptions dated to AD868 (Bor E-Ka inscription) and 937 (Sri Canasa inscription). This polity was ruled by generations of local kings, with a suffix –*varman*, whose names were unrecognisable in Cambodia, thus, possible local elites. Its location is thought to have been affiliated with Muang Sema where one associated inscription has been discovered (Hanwong 1991; Jacques 1989, 19; Vallibhotama 1997; Wangsook 2000). According to inscriptions, Hinduism was increasingly recognised alongside with Buddhism. Nonetheless, the sovereignty of local polities was to be changed eventually by the reappearance of Khmer monarchs. The re-emergence of the Khmer authority in this region links to the reign of Indravarman I (AD877-889). Subsequently, almost all of the succeeding kings individually helped to consolidate the Khmer influence in this region (Jacques 1989, 19-22; Veeraprasert 2002, 190-194). The contents of the inscriptions left by the Khmer kings often concern the issues of ritual services made to the gods at local temples and the praising of the kings. The distribution of these early Angkorian inscriptions coincide with the early constructions at the sites that would become Khmer centres or complexes such as Phnom Wan (Jacques 1989, 20), Phimai, and Phnom Rung (Jumprom 2005, 31; Suksvasti 1988) (Figure 3.17).

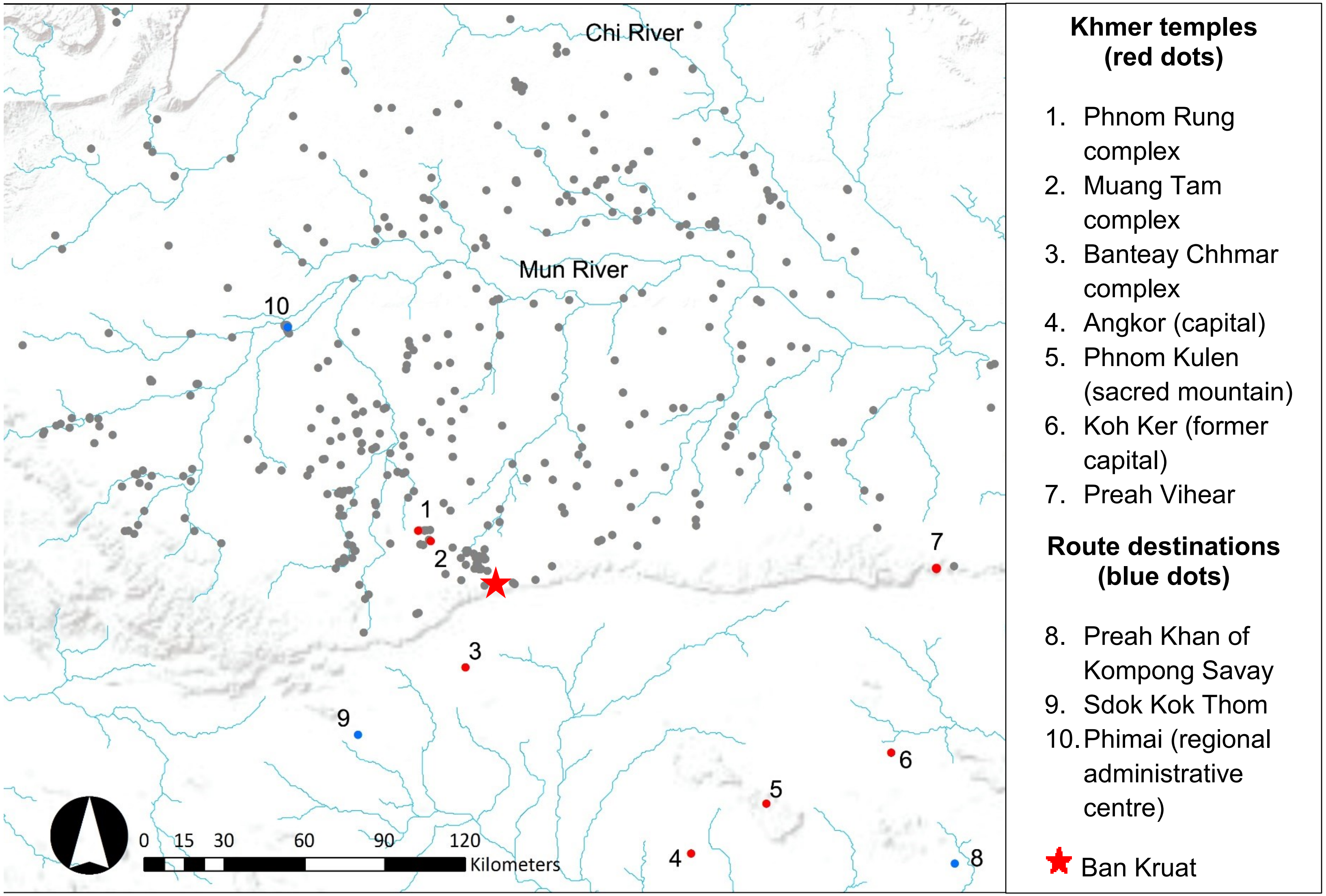


Figure 3.16 Map shows the Angkorian period archaeological sites along the Mun and Chi River system and in Cambodia

Political development at the end of the 10th century AD led to a firmer establishment of the Khmer kings in lower Northeast Thailand. An increase of royal Khmer influence may have put an end to the local kingdom of Canasapura. This is seen in the Muang Sema inscription dated to AD973 which only refers to the Khmer king, Jayavarman V. Accordingly, Khmers could have had a relatively strong hold of this polity, possibly via more peaceful approaches, since there is as yet no firm evidence of conflicts. The long-established relationship between lower Northeast Thailand and Cambodia must have facilitated the political reappearance of Khmers. The activities in the northern territory were probably encouraged by the ongoing economic and social growth in the core area during the reigns of Rajendravarman II (AD944-968) and Jayavarman V (AD968-1001).

This trend continued into the reign of Suryavarman I (AD1002-1050). His expansionist attitude led him to extend his influence further to the west, to acquire more resources and open the new trade route (Hall 1975, 2011). His strategy was to fortify the foundation of Khmers in Northeast Thailand to facilitate his movement to the west by erecting the ritual temple on the *Dângrêk* Range, named Shri Shikhareshvara (Lord of the Summit) or known nowadays as Preah Vihear. This sacred place was to manifest his divine magnificence visibly over this region (Mabbett and Chandler 1995, 101). Local chiefs and inhabitants that resided around this part of the mountain are likely to have been persuaded to join his realm in return of the protection and share of the revenues (Saraya 1994, 68). Most likely from this reign, lower Northeast Thailand became an integral part of Angkor (Welch 1997, 71). This integration could have in turn made easier the annexation of Lopburi (Pakdeekham 2014, 7-11) which allowed him to participate international commerce with the western and southern states via the Thai-Malay Peninsula (Hall 1975, 1979, 2011).

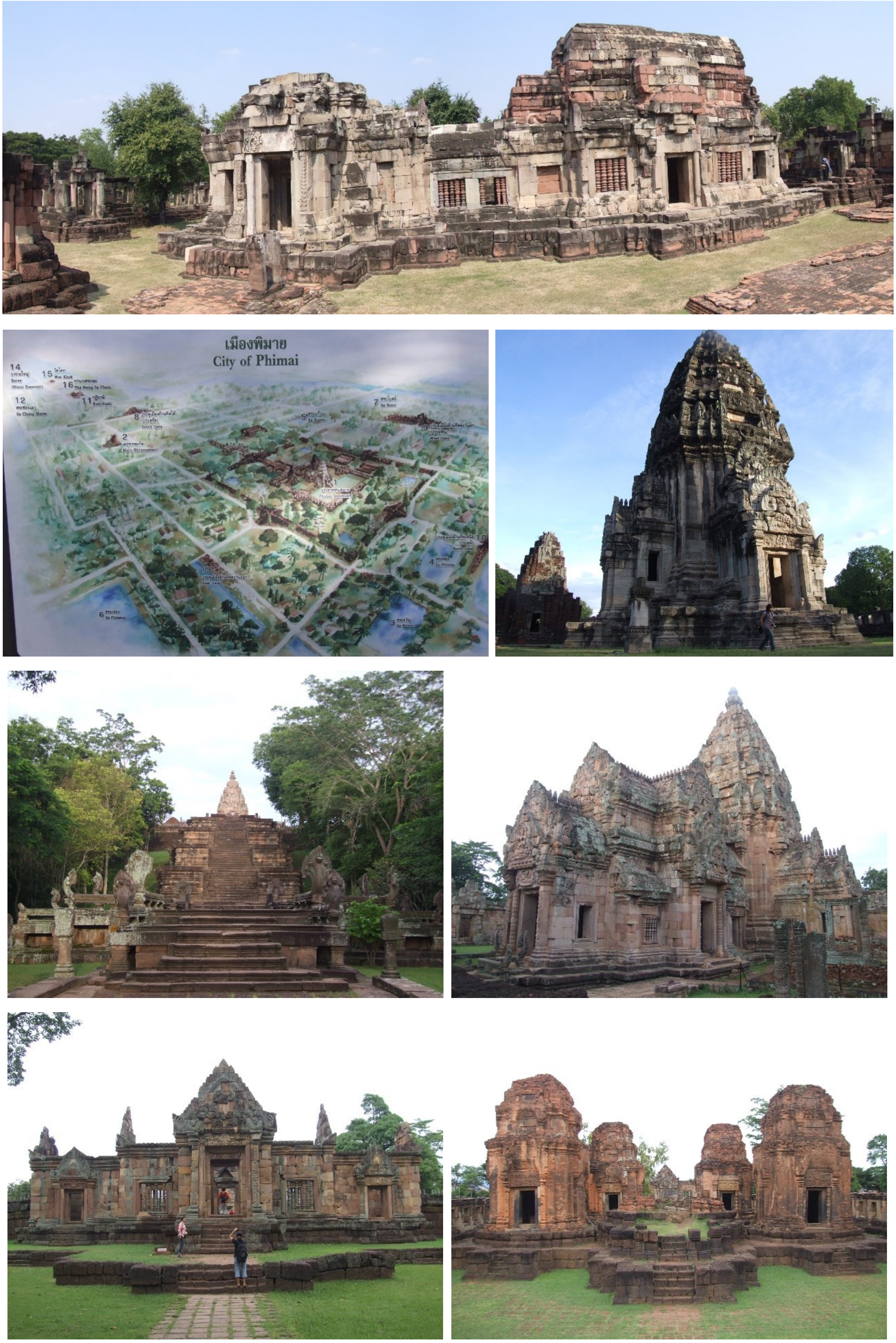


Figure 3.17 Some Khmer temples in lower Northeast Thailand. Prasat Phnom Wan (top), Prasat Phimai (middle), and Phnom Rung (below)

A transformation of Northeast Thailand, particularly the *Dângrêk* Range region, was subsequently conducted, primarily aimed at better expropriate local products. The process of integration may have involved the implantation of a similar political and economic systems that revolved around the network of temples and water management (Welch 1997, 1998). Many of settlements from the preceding periods such as Ban Prasat, Phimai, Phnom Wan, and Ban Fhai, had Khmer temples constructed along with rectangular reservoirs (*bārāy*). These water tanks may have already appeared in pre-Angkorian period in lower Northeast Thailand and became a typical hydrological feature in Angkorian period. Their main purpose were likely to have been irrigational as shown by landscape studies in the Angkor region, where water channels were discovered connecting different *bārāys* creating expansive water network (Evans and Fletcher 2015; Evans *et al*. 2013; Evans *et al*. 2007; Fletcher *et al.* 2008a; Fletcher *et al*. 2008b). However, some scholars have also proposed that the structures only had religious-symbolic meaning for they were built to replicate heaven in Indian cosmology and lacked of water distributional system (Acker 1998; Van Liere 1980). In lower Northeast Thailand, depending on which local Angkorian settlement discussed, its *bārāy* could have been conceived as either a new religious addition or a new technological replacement to existing moats seen from late Iron Age (Figure 3.4) (Limsrisakulwong 2012). The plan of settlements also changed. A square shape city plan with a surrounding moat was introduced in Phimai and other settlements in the vicinity of Phnom Rung (Jumprom 2005, 228). The newly established settlements, including Angkorian settlements in Ban Kraut, often had temples as a centre of the community and *bārāy* (Jumprom 2005; Vallibhotama 1997, 158-159; Veeraprasert 2002). Unlike the moated mounds of Iron Age sites, they were founded on the flat plain or low rectangular mounds (Veeraprasert 2002; Welch 1996, 1997). Production workshops in the vicinity of settlements were also established in various locations. For example, the newly introduced Khmer ceramic industry, focusing on glazed stonewares, that had been continued from the end of the 11^{th}-13^{th} century AD was organised within the areas of Nakhon Ratchasima, Buriram, and Surin (Chandavij and Chandavij 1989; Prommanoj 1989; Thammapreechakorn 2008). Stone quarrying was another industry to be carried out in this region (Uchida *et al*. 2009). While the organisation of the site changed, the survey in the Phimai area suggests that the site distribution pattern remained largely unchanged from the Iron Age. Most Khmer period sites still preferred to be settled in the same area as in the Iron Age or on agriculturally suitable lands, with access to nearby tributaries (Jumprom 2005; Wangsook 2000; Welch 1997, 1998; Wongdsapaiboon 2012). This survey also found that several new sites appeared in the uplands, probably associated with the iron production industry (Vallibhotama 1997, 159; Welch 1996, 75).

The construction of Khmer structures, especially temples within the settlements, served various purposes for the socio-political integration. At the already occupied sites, this was to symbolically and politically merge them into the Khmer administration with a significant modification in the water management system. Conversely, the foundation of temples and *bārāy* at the unoccupied lands would have made them inhabitable and exploitable by allocating people from the vicinity or from elsewhere to form a larger functioning settlement. Nonetheless, in both circumstances, most important function of the temple is likely to have been to act as an administrative and redistributing centre for the community which helped to maintain a connection with Angkor. This issue will be elaborated on the following section.

While articulated in temples, the role of Khmers in the region during the 9th-11th century AD appears to have been primarily economic in nature. Most Khmer activities essentially involved ritual service and economic exploitation rather than administrative issues; however, the outcome of the activities was the decline of local sovereigns such as Sri Canasa and Lopburi. Overall, Northeast Thailand was initially only a passive recipient of the Angkorian authority. The involvement of lower Northeast Thailand in the political administration would increase after the 12th century AD when a succession of kings who ruled Angkor came from the Mahidharapura royal family (early 12th–early 13th century AD) which had its root in this region (Suksvasti 1990, 42-44). The region consequentially advanced significantly in this period. Phimai was designated a regional administrative centre of this western territory, while Phnom Rung/Muang Tam, large ritual and urban complexes, located only 40 km northwest of Ban Kruat, and Phnom Wan were expanded and became powerful ritual and administrative centres in their areas.

The following reign of Jayavarman VII (AD1181-c.1218), who ruled the Empire at its apogee in the 13th century AD, saw the last strategic improvement in this region. The road system was improved presumably based on the pre-existing ones; this included the northwestern route that connected Phimai to Angkor (Hendrickson 2009, 2010, 2011; Lertlum *et al*. 2008; Tansalawong *et al*. 2007). To ease the travel, he also placed 17 resthouses (*Dharmasala*) along this particular route (Lertlum *et al*. 2008) (Figure 3.18). The route helped further strengthen the administrative control over the western territory as well as better the transportation and circulation of revenues across the Empire. The hospital was another infrastructure introduced to the region (Figure 3.19). A study of the relationship between the hospitals and Khmer settlements (Wongdsapaiboon 2012) strongly suggests that one hospital was located within a 3km radius of the nearby settlements or villages they were attached to. The king also sent his son to be a lord of

Lopburi and an image of Jayabuddhamahānātha implying an increasing importance of this location to Angkor.

Figure 3.18 Prasat Ta Muen, one of 17 resthouses on the Angkor-Phimai route

Figure 3.19 Prasat Sra Kamphaeng Noi in Surin, which is a temple attached to a hospital

It is therefore apparent that this region of modern-day Thailand was undeniably merged into the Khmer authority, whose social and cultural practices were implanted. The processes of assimilation and control might have been more peaceful than in the Angkor region (Hendrickson 2009, 102). Many inscriptions found in Thailand often recognise the names of the Khmer kings (Veeraprasert 2002). Nonetheless, this foundation of Angkor in the western territories relied heavily on the strength of the political core at Angkor (Musigama 1993, Veeraprasert 2002, 210). The epigraphic evidence from Nakhon Sawan mentions the name of the king during the reign of Suryavarman II (AD1113-1150) which is not recognised by any other inscriptions. There were also diplomatic missions, commissioned by the kingdom of Chen-Li-Fu in Central Thailand, to the Chinese court in AD1200 and 1205. These are probably evidence showing local rulers seeking to gain autonomy when Angkor was weak (Pakdeekham 2014, 10-11). Although some Khmer elements (i.e. reservoirs and temples) were already permeated in this area centuries before, new technologies (i.e. glazed stoneware) and tighter administrative system were introduced. Temple-based network system is likely to have been widely operated. The evidence suggests that the Khmer polity established its political and economic administration system in this region; however, some flexibility must have existed as the distance between the western territory and Angkor and allegiance of local elites to the Khmer kings were crucial factors.

3.3.4.2 Political, social, and economic institution of the Khmer Empire

For five centuries, the Angkorian Khmer polity maintained its status as a supraregional polity and was able to control at times large swathes of lands which were culturally and politically diverse but also rich in economic resources. The Angkor region became a large prosperous urban complex installed with various sizes of linked urban components such as state and subordinate temples, occupation mounds, rice fields, hydraulic infrastructure (reservoirs and canals), communication routes, and production workshops (Evans *et al*. 2007, 2013; Carò and Im 2012; Jacques and Lafond 2007; Ea 2010; Pryce *et al*. 2014; Uchida and Shimoda 2013; Wong 2012). Its expansionist policies merged adjacent and remote regions into the realm, and similar components were implanted onto them which is well evident in lower Northeast Thailand (Musigama 1993; Veeraprasert 2002; Welch 1998). Archaeological and epigraphic evidence indicates that the state emphasised on the public works, particularly the construction of temples and the irrigation infrastructure, and military campaigns against rebels and other polities, especially the kingdom of Champa with a possible aim to prolong the state integrity by expanding its territories and ensuring the control over resources.

For this state to retain its supremacy and integration, organisational structures were required to efficiently control and channel resources such as labour and raw materials from the controlled lands to support economic activities aforementioned. The structures were intimately linked with the religious institution, with temples playing a major role in both economy and political administration (Hall 1985; 1992; 2011; Kulke 1986, 16).

3.3.4.2.1 Political institution and society of the Khmer Empire

The structure of the polity was held together primarily through land and title grants, gifts, patronage, marriage alliances, and ritual obligation. It also depended on the ability (i.e. prowess and achievements) of the king to manipulate these political strategies to control the political members. The Angkor region served as a centre of religious, political, and economic institution and seat of the king. The control of the core area may not have been of a great concern for the king as it was there that the full royal power could be exercised more directly. However, distant regions might have been problematic for the administration, with higher risks of rebellion and political instability. Regional administrative centres were established likely to address this issue and help to control land more flexibly and keep local elites in sight, for example Phimai (Vimay or Vimaya) and Lopburi (Lavodaya or Lavapura) whose responsibility was to administer the western territories (Hall 1975, 2011).

The administrative division involved *pramān/viṣaya* (province?), *-pura* (city or urban centre), *sruk* (district), and *grāma* (village) (Jacques 1986, 329; Mabbett and Chandlers 1995; 167; Sahai 1977b; Vickery 1998, 327). This division is likely to have been hierarchically maintained by a king (*-varman*) and functionaries (*rājakāryya, kāryya, taṃrvāc,* and *khloñ*). The officials, who may have been appointed by the king and/or drawn from local elites, would manage any social or political matters and ensure the circulation of revenues in the system. This was possibly for an ease of the administration and collection and mobilisation of tax and revenues, which were mainly grain and other commodities (Mabbett and Chandlers 1995; 166; Sahai 1977a, 1977b; Sedov 1978, 121). Additionally, each level was administered by the chief/elite (*khloñ viṣaya, khloñ sruk*), probably based at the temple of each division. These classes ruled over the commoners, including small landowners, merchants, professionals, for example artisans (weavers, spinners, potters), and slaves, who were either attached to the temple (*vrah kñuṃ*) or to other sectors (*kñuṃ*) (Hall 1975; Jacques 1986; Mabbett and Chandlers 1995; Sedov 1978; Vickery 1998).

Arguably, temples were erected to legitimate the right of the members of the Khmer authority to rule over the lands through the use of collective ritual. These temples, likely to have been organised by members of elites who were priests or clergy, functioned as an administrative and redistributive centre for the settlement (Hall 1992, 2011; Sedov 1978, 114). Giving the control of temples, particularly local temples, to elite members, these could have access to more shares of the revenue in exchange for loyalty. With possibly 3,000-3,500 temples built at the peak of Angkor, this created an extensive network of temples of different hierarchical levels that held the state together (Sedov 1978; Lustig 2009, 253).

3.3.4.2.2 The imperial Khmer economy

There is a general consensus that the Khmer economy and its wealth generation relied strongly on the agriculture, especially rice, supplemented by commerce and taxation (Jacques 1986, 330; Mabbett and Chandlers 1995, 175; Sahai 1977a; Stark 2006, 160). Arguably, it was the technological advancement of agricultural irrigation and the economic and political organisation that allowed the maintenance of the extensive political geography of the empire for nearly 600 years. Hydraulic networks of *bārāy*, canals and water channels (Evans *et al.* 2007; Pottier 2000; Sonnemann 2011) were developed to support intensified and extensive wet rice agriculture. As a result, Angkor's water management system carried a vast irrigational network that connected canals, embankments, and reservoirs. The purpose of these structures would have been to maximise the capability of lands for the agricultural production and increase productivity. The food surpluses produced supplied the Angkorian population with an estimated 1 million inhabitants for the capital at Angkor only (Groslier 1979, 190-191; Acker 1998, 21-22), and funded local and state projects. The high demand for rice may be inferred, for example, from the 12th century AD inscription of Preah Khan (K.908) stating that approximately 40,000 tons of rice were supplied annually to this temple (Lustig 2009, 220). Also, massive state construction projects of elaborate temples (e.g. Angkor Wat, Bakheang, and Preah Ko), urban complexes (e.g. Angkor Thom, Banteay Chmar, and Preah Khan of Kompong Svay) or western and eastern *bārāy* would have required tremendous amounts of rice for the large numbers of workers and their families.

Meeting the increasing demand for rice required a strong political and economic organisation articulating components, such as land, labour, product management, and taxation. Labour intensification in rice agriculture required the considerable numbers of labourers for working in the fields and nurturing and processing rice, but also for manipulating the water supplies (e.g. the constructions of canals or reservoirs) (Fuller and Qin 2009). Continuing from the pre-Angkorian period, the Khmers, particularly the ruling classes, managed this production activity through the elaborate network of temples that acted as political-economic agents controlling the production, storage, and redistribution of the product. Since the economy of the empire appears to have been non-monetary, the network of temples would improve the redistribution of resources across the territories. They worked on the basis of a stratified political order connecting village temples to state temples (Hall 2011, 162).

According to this model, the expansion of the Khmer's influence to neighbouring areas, including northern and western territories, aimed to increase the agricultural productivity, especially rice, and other resources (e.g. metals, stones, and forest products) by acquiring new lands and people. The Khmer also sought to open new commercial routes through the processes of cooperation and coercion of regional landholding elites, or through control over unoccupied lands (Saraya 1994, 68; Lustig 2009, 227-228; Hall 2011, 159-209). The occupation of new lands for rice farming is apparent in the Mun River Valley, where the distribution of temples matches the areas environmentally suitable for the agriculture (Welch 1998, 213). Moreover, as the area had been populated since the Iron Age, this created an opportunity for accumulating more labour. After gaining control over new lands, the kings tasked elites either from Angkor or local to establish a temple which would serve as the administrative and redistributive centre for each settlement. These leaders or elite families supervised politically and economically all activities within the community boundary (Ricklefs 1967). The inscriptions suggest that people and necessary materials were supplied, likely from Angkor or regional centres, to ensure the successful establishment of new settlements. These people (e.g. field labourers, artisans, and dancers) endowed to the temple were assigned to specific tasks depending on their speciality, for example field labourers who then worked in the field and other related assignments including land clearance and the construction of local irrigational system. They would therefore have been a main workforce mainly attached to the temple. Further labour force could have been provided by commoners who probably worked as *corvèe* (Lustig 2009, 229). These two sources of workforce for productive activities would have contributed much to the economy. Rice produced by these two labour groups might have been collected as tax and distributed locally as well as transported to larger settlements and, potentially, Angkor.

Land management is another essential basis of this economy as the control over lands allowed the control over the resources and the attached workforce (Ricklefs 1967, 412-413). The lands might have been largely owned by clan groups and was exchangeable or purchasable. The king is seen to have had authority to offer lands to his subordinates as payment or in return for their loyalty, and to occasionally intervene with this land ownership when disputes emerged (Ricklefs 1967). Within this system, temples would play an essential role in expanding the territories, establishing new settlements, administering activities, organising and assigning the workforce, collecting tax (in forms of products or *corvèe*), storing and redistributing products, and, most importantly, connecting all communities to the capital at Angkor. In return, each temple and community leader might have gained tax immunity and access to the state's goods, prosperity, patronage, and recognition.

Thus, agricultural activities around intensified rice production appear to have been a foundation of the Angkorian economic and political structure (Hall 2011, 177). The networks of temples played a key role for administration and mobilisation of resources, effectively creating a centralised economic system. The success and efficiency of Angkorian systems in organising labour and producing and redistributing resources may also be seen in the continuous constructions of state temples and infrastructures and the waging of wars, mainly with Champa, throughout its history. However, the need for surpluses in order to finance civil and military projects eventually posed a problem to Angkor, thus, increasing its vulnerability. Temples and irrigational structures were commissioned across the territory, and this required an enormous and steady supply of resources, essentially labourers, probably slaves (Dumarçay and Royère 2001, 7), and construction material. Revenue including lands, precious metals, and slaves were used to finance the projects (Dumarçay and Royère 2001, 8-9). The extensive construction programmes in the reign of Jayavarman VII may have initially weakened the economy (Dumarçay and Royère 2001, 8). The serious climatic fluctuation at Angkor by the 14th century AD further crippled the state when the adaptive strategies, which involved the modification of irrigational system, were ineffective at preventing intense floods and droughts (Buckley *et al*. 2010).

3.3.4.2.3 Craft production and its organisation in the Angkorian period

As noted throughout this section, epigraphic evidence consistently demonstrates the importance of land and agriculture for the empire. In this thesis, however, it is further argued that the production sectors involving fundamental materials (e.g. stone, laterites, and metals) and objects (e.g. ceramics, fabrics, and ornaments) may have played an equally essential role in accomplishing and sustaining socioeconomic and political activities (e.g. trade, constructions, warfare, and daily life or even agriculture). The archaeological and epigraphic evidence clearly demonstrates that these materials were constantly required by almost all sectors in the society (Dumarçay and Royère 2001; Lustig *et al*. 2007, 25; Thammapreechakorn 2009; Wong 2010). Given the intensification of activities requiring these materials, one can imagine a considerable scale of demand. Nevertheless, the production, organisation, and distribution of non-perishable materials and the role of production technologies in the Khmer industry and state are not well understood. One problem may lie in the academic focus of pre-Angkorian and Angkorian research that has heavily focused on epigraphic, architectural, and artistic evidence. Furthermore, the corpus of inscriptions are not of very informative of these aspects; although, it seems to be clear that exchange and temple transactions with objects took place (Lustig *et al*. 2007). Even though references to metals are relatively scarce, some inferences may be drawn from other productions (i.e. stone and ceramics) that have received better higher-resolution studies.

A key area to investigate aspects of the organisation of production is from the study of ceramics. This group of objects have been described as one of the most important commodities in the empire. Khmer ceramic were only circulated within the empire, and the most diagnostic wares include glazed stonewares. Their origins were heavily influenced and guided by the adoption and imitation of the Chinese ceramics and their technologies, which were considered a premium merchandise (Brown 1988, 42; Groslier 1983). Their industrial remains and finished objects provide direct evidence for archaeologists to look into their economic system (production, distribution, and consumption).

Ceramic production concentrated within the political core areas, but few sites were also documented in lower Northeast Thailand (Wong 2010, 59) (Figure 3.20). However, the major production zones were on two areas; the first kiln group was located on Phnom Kulen and west of the mountain and the second one north and south of the *Dângrêk* Mountain Range (Ea 2010, 42; Wong 2010, 59). The first group was in close proximity of Angkor and is thought to represent a cluster of "state kilns" producing the high quality products which some types, such as green glazed and architectural ceramics, which were produced exclusively for the royal family (Wong 2010, 73, 279). The second group was located in lower Northeast Thailand and Northwest Cambodia. Their products included green glazed, but also brown glazed wares, new types of ceramic commonly found across the imperial territories from the late 10th century AD. They have been hitherto not found associated with the Phnom Kulen group but were evidently produced at the kiln sites in Teap Chei, near Angkor (Hendrickson 2008).

The industrial activity at and near Phnom Kulen is thought to have commenced first, probably during the 9th century AD (Ea 2010, 230-231). Then, in the 11th century AD, the *Dângrêk* kiln group was established as suggested by the kiln sites in Buriram (Thammapreechakorn 2009, 284). Comparative studies between two groups indicated that the production practices and products manufactured were considerably different (Thammapreechakorn 2009, 284). The "*Dângrêk*" group appears to have been more developed, as reflected in the kilns being larger and having different designs (Ea 2010, 232; Thammapreechakorn 2009, 174-176; Wong 2010, 70). Moreover, more varieties of products were manufactured by this group. The differences in the kiln technologies, production traditions, and products between Phnom Kulen and the *Dângrêk* region could be used as a basis to suggest that different production traditions were practised and more than one group of potters were active. Adding the Teap Chei kilns into this picture, different kilns may have held different statues and served different purposes. Certain kilns are likely to have been attached to the royal family (i.e. Phnom Kulen group) with a responsibility to produce high-quality products. Others, such as the *Dângrêk* and Teap Chei kilns may have been to serve local demand. The latter kilns might have been under the supervision of local temples; although, some scholars assumed that the *Dângrêk* kilns, especially those in Thailand might have been directly controlled by Phimai or Phnom Rung for this area was the stronghold of the Mahidharapura Dynasty before ruling Angkor.

Ea (2010, 231) proposed that the location of kilns across the territories depended on where the political core was at the time. Phnom Kulen was once a stronghold of Jayavarman II before he moved to the new capital in which the new production might have established. The emergence of the *Dângrêk* kiln group, when their understanding of ceramics became more mature, may be a response to the Khmer expansion in the 11th century AD and the emergent Mahindhrapura royal family in the 12th century AD (Thammapreechakorn 2009, 143). Additionally, it is plausible that the locations of the workshops was not only dependent on the political situation, but also the suitability of the locations (i.e. availability of suitable clay). As a matter of fact, both ceramic production zones were in areas well supported by essential resources, including clay and fuel, and transportation system.

In terms of the distribution of the products, according to current evidence, prior to the 11th century AD, ceramics were likely exported from the Phnom Kulen group. Then in the early 11th century AD, the production centre in the northwest of Angkor introduced the considerable amounts of ceramics, especially brown-glazed wares, to the market. Other kilns, such as the Teap Chei kilns also participated in producing similar products. These two production districts might have been responsible for distributing ceramics to most settlements. The production at Phnom Kulen is likely to have focused on other high-quality products for elites and royal family. Notably, since there has been no ceramic kilns found so far in Central Thailand, one may look at the workshops in lower Northeast Thailand to be a major supplier. This is quite plausible when considering that most ceramics found in association with the Angkorian archaeological sites in Thailand are stylistically related to this district (Thammapreechakorn 2009, 48-50). According to current evidence in Thailand, suitable clay sources (see section 3.2 for further discussion) and the more political stability in lower Northeast Thailand and closer distance to Angkor, compared to the lands further to the west, may explain the decision to establish the ceramic workshops in lower Northeast Thailand.

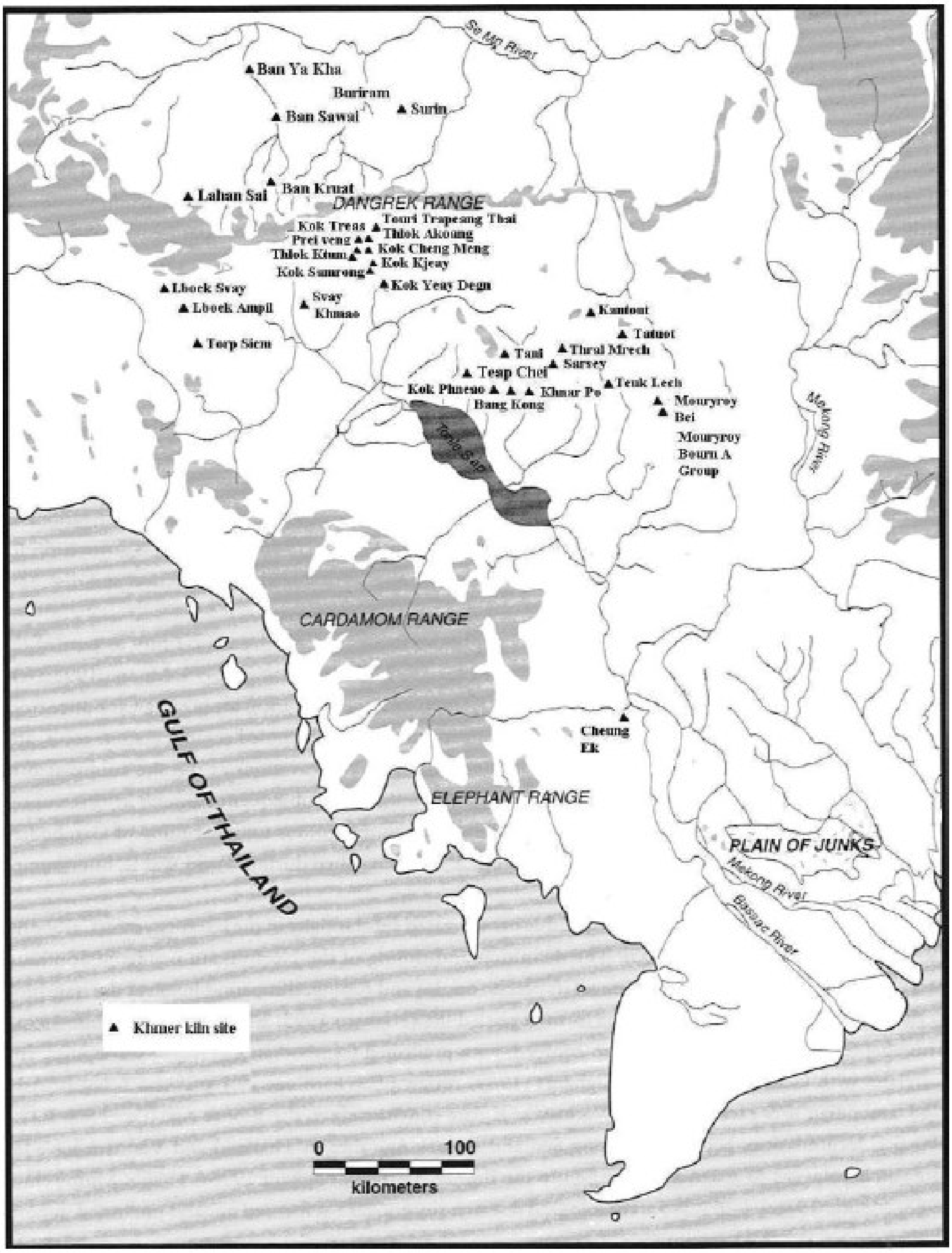


Figure 3.20 Distribution of Angkorian kiln sites

(Image: Wong 2010, 74)

More information about raw material exploitation can also be derived from the study of building material. Sandstone, in particular, was a fundamental material for construction (i.e. for the main structure and decorative component) and arts. A series of studies have posited that the Khmer artisans exploited stone from quarries in the vicinity of their construction sites or workshops. The Angkor monuments and statuary have been suggested to have a link with the sources of sandstone at Phnom Kulen and nearby Koh Ker where multiple quarries are documented (Carò and Douglas 2013; Carò *et al.* 2010; Carò and Im 2012; Uchida *et al.* 2007; Uchida and Shimoda 2013), which would have supplied the city of Angkor using waterways (Uchida and Shimoda 2013, 1162). Likewise, the study at various temples in the Thai side reached a comparable conclusion, i.e. exploitation of local sandstone outcrops were sourced, as inferred by the petrographic study of the sandstone used in the temple construction (Uchida *et al*. 2010). Quarrying marks left on sandstone outcrops, such as at Ban Kruat, Ta Phraya, and Si Kiew also complements this provenancing.

Laterite was another material intensively used for the construction, but mainly as a foundation of the building or as walls of reservoirs. Very few studies have been done to provenance the sources. As laterite is widely abundant, the sources of laterite are generally assumed to have been exploited from nearby deposits close to the construction sites.

Metals have been recovered archaeologically as well as referred by documentary evidence. Copper, tin, lead, silver, and gold are common in the inscriptions as temple offerings or as artefacts, such as ornaments, utensils, and decorative components for architecture and statuary (Bunker and Latchford 2008, 2011; Chou 1967; Cort and Jett 2010; Diskul 1966, 58; Groslier 1981, 10, 12; Ta). They were typically associated with the religious section and the high status classes (Bunker and Latchford 2008, 2011; Lustig *et al.* 2007, 20). Economically, metals, particularly silver and gold, played a significant role as a transaction medium along with other commodities, as the Khmer Empire is thought to have been non-monetary state (Hall 1975, 321, 2011, 178; Sedov 1978, 123-125).

Even though, the use of metals in the empire is evident, the all-important dimensions of metal production, manufacture, craft organisation, workshops, and craftspeople are almost absent from textual sources. Archaeology does offer relevant information, but this is still very fragmentary. The core area of Angkor seems to have lacked metal resources, except for iron which was and still is abundant at Phnom Dek (Bronson 1992, 75). Arguably, this could have forced Angkor to import most metals from other controlled areas or via commercial activities in which merchants traded gold and silver (Chou 1967; Hall 1975, 321).

The evidence presented so far, although fragmentary, allows some provisional inferences about the broader economic system. It seems that the location for the workshops was largely influenced by the suitability and availability of resources. Additionally, the shifts in political centres and territorial expansion also influenced the establishment of workshops for different industries. The workshops, especially for ceramics appear to have been concentrated on particular areas. The products would then be exported to the consumers. Considering the existence of a hierarchy of interconnected temples and social classes, it seems reasonable to suppose that different types of production sites would have existed: some would be more directly attached to the state, probably controlled by the royal family or state-level temples, and others would be more local.

Some issues, including the administration and control over the activities, remain largely elusive. A temple-based economic model has been suggested as a potential model (Welch 1997; Wong 2010, 278-288), while the epigraphic evidence is not substantially informative. Temples might have been responsible for administering the activities and circulated products as discussed in the section 3.3.4.2.2. Merchants and marketplaces may have also played a crucial role, along with temple networks, in distributing and exchanging goods among members of the society (Hall 2011, 178). The reference to them in some inscriptions suggests that Angkorian trade and transaction was not fully controlled by temple networks and a ruling power.

The inscriptions refer to the existence of artisans, although only in rare occasions. They appear to have worked as temple servants. As specialists, some might have gained higher status or become chief or master of a group of craftspeople (Lustig 2009, 78; Sedov 1978, 125). Sedov argued that artisans, such as goldsmiths was part of privileged kinship-cum-professional group (Sedov 1978, 120). Nonetheless, it is still unclear whether artisans would have been full-time specialists, or whether they were expected to work in agriculture too. Commoners and *kñuṃ* may also have participated in craft activities, possibly as workforce under supervision of master artisans (Sedov 1978, 125).

3.4 Summary

The archaeological record of lower Northeast Thailand allows us to map the change in organisation of craft production as society had become increasingly complex through time. In the Iron Age, an increase in labour efforts was there to support the agricultural intensification and civic construction. Craft production saw an increase in specialisation and the variability in organisation according to materials produced. Textile seems to have been locally, whereas pottery, salt, and bronze were probably manufactured at specialised sites. A shared pottery tradition is a good indicator for regionalisation of production. As not all settlements participated in the production, exchange networks served as a mean to acquire and circulate commodities. The restriction of commodities would provide an opportunity for local elites to generate wealth via controlling the economic organisation.

The evidence is not clear for the subsequent period, but the situation may not have changed drastically. A few strands of evidence point to the early manipulation of religious ideology to persuade followers. However, societies probably retained their own traditions, including the production systems.

A drastic change came in the Angkorian period. Lower Northeast Thailand was integrated into the centralised political and economic realm of Angkor. Temples became the effective support for the empire which helped to control and channel resources. Craft production appears to have spatially concentrated on particular areas and supported by expansive communication networks in order to distribute the products.

Chapter 4 Technological and historical background on iron and its production in Thailand from the Iron Age to the Angkorian period

4.1 Introduction

As the socioeconomic and political factors were reviewed in the previous chapter, the purpose of this chapter is to explore the equally important factor assumed to have guided iron production in Ban Kruat. The technical background of iron production technology is introduced here to demonstrate the constraints that imply iron technology must be performed within a large but still finite chemical and mechanical envelope. This chapter introduces also the current state of archaeological, historical, and ethnographical knowledge about the social and technological environments surrounding pre-industrial iron in the Thai context (Iron Age – Angkorian period).

In the last section of this chapter, the hypothetical models for the organisation of iron production in lower Northeast Thailand, constructed based on archaeological and technological information reviewed in Chapters 3 and 4, are proposed. To what extent these models could improve our understanding about iron production in Ban Kruat will be evaluated and tested in Chapters 8 and 9 after discussing both archaeological and archaeometallurgical evidence in Ban Kruat (Chapters 6 and 7).

4.2 The ironmaking process: understanding how raw metal is produced

Ancient iron, in general, was produced by two main methods: direct/bloomery and indirect/blast furnace smelting. The first method is characterised by iron being produced in a solid state (i.e. the bulk of the iron produced is not molten or liquid): a bloom, a mixture of low-carbon metallic iron and slag, is the resultant product. In contrast, metallic iron in the indirect method is produced in liquid form, typically in the form of carbon-rich cast/pig iron; normally, this needed to be decarburised before it can be turned into objects such as tools and weapons, as cast iron is hard but very brittle.

Archaeology has shown that the direct smelting method was the one adopted by almost all smelters in the Old World in the early stages of iron production (Craddock 1995). Around mainland Southeast Asia, regions such as India and China saw bloomery iron production being practised (Gullipalli 2014; Mei *et al*. 2015). At the same time, early use of indirect smelting is well documented in ancient China, possibly since the 5th century

BC or earlier (Han and Chen 2013; Mei *et al*. 2015, 226), whereas European smelters became familiar with this technology at least one millennium later (Rostoker and Bronson 1990, 101).

In mainland Southeast Asia, it is widely agreed that iron made its appearance around the 5th century BC (Bellwood 1994, 116; Higham 2014; Pryce 2014), and the origins of regional ferrous technology may have intimately been linked with two exotic sources: India and China. The transmission is presumed to be part of social and commercial interactions between these two regions and mainland Southeast Asia (see section 3.3.1). Currently, evidence for early production (Hudson 2012 in Pryce 2014; Mokhtar 2012, Nitta 1991, 1997) and use of iron (Bennett 2013; Biggs *et al*. 2013; Pryce *et al*. 2006; Stech and Maddin 1988, 171) seems to be dominated by those associated with bloomery ironworking method; although, remains of cast iron have been reported in small quantities and uncertain contexts (cf. Biggs *et al*. 2013). Since vast expanses of ferrous archaeometallurgical remains have not been fully understood, the technological links are currently in debate. However, craftspeople might have been stimulated by different sources depending on their locations. For coastal and hinterland areas of Thailand, Cambodia, and Vietnam, excluding its northern parts, the Indian subcontinent may be a potential candidate for the origins of ferrous technology. This proposal is thought to have been correlated to the long-range social interaction with India (Bellina and Glover 2004) where bloomery smelting was a dominant practice (Gullapalli 2014). This is supported by current evidence for early ferrous metallurgy that, although fragmentary, largely conforms to this method (Bennett 2013; Bronson 1985, 212; Nitta 1991, 1997; Stech and Maddin 1988, 171; cf. Biggs *et al*. 2013). On the other hand, the technologies from China may have influenced those in northern parts of the region (e.g. Laos and northern Vietnam) due to their proximity (Pryce 2015 pers.comm. 27 July).

For Thailand and Ban Kruat, evidence for early production and use will be reviewed in detail later; it is advanced here, however, that ancient iron production appears to have been consistent with bloomery smelting production, even if small traces of cast iron may be found (see section 4.3.1 and 7.2.4.1.1). The use of the indirect smelting method to purposefully produce iron was possibly adopted as late as the 17th century AD, introduced by Chinese smelters (Bronson 1985, 215). On this basis, the discussion on the general principles of how iron was made will focus on the direct/bloomery smelting method.

To produce iron by this method, certain universal technical parameters have to be met. This makes cross-cultural comparisons of iron production practices possible. As a region-specific archaeometallurgist, it is to attempt to understand the thermodynamic constraints of a particular geological context, so this variation can be stripped out to reveal the technological choices made within the operation envelope. The socioeconomic and political setting of each society can intervene and manipulate this variability in practising ironmaking. This may be best portrayed by very wide variety in making iron in sub-Saharan Africa. Understanding how iron is made in principles helps to better reconstruct ancient iron technologies from metallurgical remains encountered. Moreover, it may offer an indirect reflection of technological styles and identities of practitioners or society (see Chapter 2).

The principles of the direct smelting process have been discussed at monograph depth by other scholars (e.g. Craddock 1995; Joosten 2004; Pleiner 2000; Rostoker and Bronson 1990; Tylecote 1987). This chapter presents a broad overview of the technology and operational sequence emphasising the primary process of ironmaking. Primary (smithing of blooms) and secondary smithing processes (forging of objects) are discussed only in brief as related remains were also found but in a small number and confined to specific sites (see section 7.3.2.1).

Iron ores tend not to be pure concentrations of iron oxides but rather the chemical and/or mechanical combination of iron minerals with impurities or gangue (i.e. MgO, SiO_2, Al_2O_3, K_2O, CaO, TiO_2, and MnO) (Rostoker and Bronson 1990, 44-45). Typical iron ores, which are relatively widespread across the Earth's surface, consist of an oxide group (i.e. magnetite (Fe_3O_4) and haematite (Fe_2O_3)), an oxyhydroxide group (i.e. goethite (FeO(OH) and limonite ($FeO(OH)\cdot nH_2O$)), and a carbonate group (i.e. siderite ($FeCO_3$)). In bloomery smelting, ore is preferred to ideally contain more than 65 wt% FeO with gangue given that iron oxide is needed to be sacrificed in order to create slag during the smelting (Rostoker and Bronson 1990, 92). Although a richer ore is preferred, smelters' appreciation of ore depends also on how easy it can be obtained and processed. For instance, magnetite ores, although they can contain much iron, are also very dense, thus, being difficult to be reduced without some preparation (Killick and Miller 2014, 250).

Winning metallic iron from iron ores, iron has to be separated from its bound oxygen, and remaining impurities have to be removed from the metal as much as possible. Mechanisms involved concern a reducing reaction (i.e. removal of oxygen bound with metals in their oxidised states) and the formation of slag (i.e. to remove containing impurities).

To produce iron in this setting, some parameters need to be fulfilled. Firstly, an environment is required to be low in oxygen and have high proportion of carbon monoxide (a reducing agent). This condition then facilitates the separation of oxygen from iron oxides. Secondly, sufficiently high temperature, which can be as high as 1,300-1,400°C, but 1,150-1,200°C were what most ancient furnaces could maintain, has to be sustained until the completion of smelting operation. The sufficient temperature and adequate time allow the required reaction to take place.

In furnace smelting, the furnace charge is comprised of fuel, ore and potentially flux (mention ceramic degradation, unintentional fluxing). In many cases the charge components are heavily processed prior to the smelting operation. The preparation of ore involves concentrating iron minerals by mechanically removing (e.g. crushing, sorting, and, washing) unwanted gangue minerals (i.e. quartz). Crushing minerals to an appropriate size is often desired by smelters to increase the surface area for a given volume, promoting increased contact with circulating hot reducing gases. Prior roasting of some ores in an oxidising atmosphere may be necessary to drive off volatile impurities and to increase porosity, thus augmenting surface area. Some benefits can be obtained from roasting ores. First, it eases the crushing of ore into smaller pieces. Secondly, it can change any iron oxyhydroxide and carbonate into oxides which are probably easier to be worked (Rostoker and Bronson 1990, 52; Joosten 2004, 11).

As the smelting process begins, the following chemical reactions can be theoretically expected. The air is channelled into the furnace, introducing oxygen into the atmosphere, through tuyère(s) either by forced draft by bellows or natural draft (e.g. chimney effect or wind-powered furnace (Juleff 1998)). The air then helps the carbon-rich fuel, typically charcoal, to burn in the presence of oxygen releasing the heat and carbon dioxide (CO_2) through the incomplete combustion. This gas then reacts with unconsumed charcoal to produce the reducing agent, carbon monoxide (CO) necessary for further reduction of iron oxides in ores. This reaction is known as “Boudouard reaction”.

$$C + O_2 \rightarrow CO_2$$

$$C + CO_2 \rightarrow 2CO$$

The CO subsequently reacts with iron oxides in the ores, extracting oxygen from them. These oxides are reduced successively from haematite to magnetite, wüstite, and finally metallic iron. The ore is progressively reduced as it travels down the furnace, and iron initially forms above the combustion zone where is high in oxygen.

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$$
$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$$
$$FeO + CO \rightarrow Fe + CO_2$$

Although iron is produced, the formation of iron in this system faces some technical issues. Firstly, iron has to be separated from the co-existing impurities in the ore. Secondly, since iron is formed near the combustion zone where oxygen is injected, it is at risk of being re-oxidised. Lastly, iron is formed in the solid state; therefore, a means to consolidate particles into a larger mass of iron is needed.

The formation of slag becomes a solution for these issues. The main function of slag is to serve as a collector of impurities introduced by the smelting components (e.g. ores, fluxes, and technical ceramics). The silica and alumina, which are the major non-ferrous constituents, prove very difficult to be removed as they melt at the temperatures of 1,713°C and 2,072°C, respectively, which ancient bloomery furnaces could not reach. However, they, along with other gangue elements, can be removed by bonding with iron oxide in the ore to form the slag. This mixture can be formed at achievable temperatures (1,150-1,300/1,400°C) and remain liquid for separation to take place. These components begin to crystallise upon cooling and form the crystals according to the composition of the residual melt derived from ores, technical ceramics, and fuel ash used (Bachmann 1982, 9-13). The most common crystals are fayalite (Fe_2SiO_4) and unreduced iron oxide or wüstite (FeO). Hercynite crystals ($FeAl_2O_4$) can also be expected (Bachmann 1982, 15-16) if the composition is saturated with alumina. Some oxides (of e.g. CuO and P_2O_5) can be reduced and join metallic iron (Desaulty *et al.* 2007; Navasaitis *et al*. 2010; Severin *et al*. 2011, 989-990).

Fluid slag is preferred by smelters as it promotes the passage of iron particles, which can then consolidate into a useable mass, the bloom. Slag, furthermore, helps to protect iron from oxidation as it moves near the combustion zone (Joosten 2004, 9). Slag is fluid when it contains FeO around 60-80% at the temperature of 1,200°C (Rostoker and Bronson 1990, 91), but slag viscosity increases as it absorbs more silica and alumina (Bachmann 1982, 19; Chen *et al*. 2013, 822). The removal of slag from the furnace as it forms can be done via two major ways: tapping it out of the furnace or letting it drain to a bowl or pit inside the furnace structure.

As iron particles coalesce together, the bloom, a typically heterogeneous mass of iron, iron alloys (mainly Fe-C), and residual slag, is eventually formed. Iron created in this method is mostly soft iron (i.e. low in carbon – around 0.05% C) mixed with some mild steel (i.e. less than 0.3% C), which is arguably preferable by blacksmiths for its workable properties (Pleiner 2000, 136). Cast iron (2-5% C) is also produced occasionally, interspersed with the mild steel. Cast iron production is favoured by a high charcoal to ore, high air rate, and strongly reducing conditions but is thought not to have been a widely desired outcome due to the difficulty/impossibility of forging such alloys (Craddock 1995, 236, 250, 2003, 232–233; Crew *et al*. 2011; Pleiner 2000, 248).

The bloom is then brought to the next stage, “primary smithing process”. In this stage, the bloom is repeatedly hammered in order to squeeze out impurities (i.e. slag) and consolidate it into homogenous iron billet. This billet is ready to be hammered into desired objects in the process known as “secondary smithing” or forging (e.g. Tylecote 1962, 1987, 1992; Pleiner 2000).

The identification of smithing activity at archaeological sites can be facilitated by the presence of diagnostic evidence related to this activity. These include hearth remains, hammerscale (expelled oxidised iron particles), spheroidal slag, and, importantly, the slag, known as smithing hearth bottoms (SHBs) or plano-convex shaped slag (PCBs) (McDonnell 1983, 1991; Serneels and Perret 2003; Veldhuijzen 2005, 216-228). This slag is created by the accumulation of expelled smelting slag remaining in the bloom or iron, hearth lining, fuel ash, flux (i.e. sand), and hammerscale at the bottom of the hearth. Morphological and/or chemical comparison between smelting and smithing slag is required to confirm its origin (Veldhuijzen 2005) as furnace slag can frequently look like smithing slag.

For the study of ancient iron technologies, in many circumstances, slag becomes the most valuable source of information allowing archaeometallurgists to effectively tackle the topic. The information slag contains is the history of the raw materials that were introduced into the system as well as the operations parameters of the smelting process (i.e. temperature, redox conditions, ore:fuel ratio, consistency). Other aspects of the operation can be inferred, such as the type of furnace and how slag was removed. The metric, structural, and chemical data obtained from slag can be assessed in conjunction with other metallurgical components to have a fuller picture of iron technology. Defining these components can reflect the choices made and recipe followed, thus, identifying tradition, practice, and identity or help to detect any chronological or potentially concurrent (social) variation in the practices within a single site and between sites or cultures (Charlton *et al*. 2010, 2013).

This research is founded on the above premises and seeks to examine slag and the less abundant metallurgical components (e.g. technical ceramics and ore fragments), and to assess the data obtained through morphological, microstructural, and elemental analyses. Integrating these technical data into a broader archaeological context will allow the author to address the questions of why and how particular technology(ies) or practice(s) was/were chosen and organised.

4.3 Iron and its production in Thailand: an overview

Since its appearance, iron has retained a prominent role in the political-socioeconomic realm of lower Northeast Thai societies, as a metal extensively used in agriculture, civic engineering projects, and warfare. Its significance is reflected in the wide distribution of this metal in many Iron Age sites. Iron artefacts and production remains, particularly smithing slag, are among common archaeological finds; although, they are not as abundant as ceramic fragments. It has long been appreciated that information they contain have the potential to bridge technological and social worlds, thus enriching our understanding of past societies. However, iron-related finds are still largely overlooked resulting in underdeveloped understandings about this metal and its social role (Chaikulchit 1997, 1; Pryce 2014, 10).

Our current knowledge of this metal is dominated by artefact studies. This may be because the excavations have focused mostly on cemeteries and ritual and habitation sites where finished objects are more common. On the contrary, evidence for primary and secondary production, particularly slag, has rarely been investigated. Even if sites are visited, the information reported is often very limited. The technological aspects are not examined in detail and often presumed without considering variability. The oversight may be because of lack of specialists and experience, and examination methods can be costly and laborious.

Even though some problematic issues are faced, the available fragmentary evidence has still unveiled useful information on the ancient production and consumption of iron in Thailand.

4.3.1 Iron before the rise of Angkor (5th century BC-9th century AD)

As introduced at the beginning of the previous section, current evidence in Thailand indicates that iron appeared around the mid-first millennium BC (Bennett 2013, 108; Pryce *et al*. 2006, 296; Higham 2011b) and had its origin connected to the Indian subcontinent (see section 4.2).

Iron appears to have been adopted rapidly by regional populations, at least in coastal areas and lowlands, within the first two centuries. Numerous iron artefacts unearthed at many Iron Age sites are indicative of this spread (Higham and Thosarat 2012, 167-221). The spread of knowledge was possibly accelerated by multi-regional exchange networks and population mobility (see section 3.3.2). In lower Northeast Thailand, the introduction of this metal is concurrent with steeply increasing social complexity (see section 3.3.2 and 3.3.2.1). Iron is also likely related to the intensification of agriculture, the construction of water management, and the emerging violence (see section 3.3.2) due to its superior properties in making implements and weapons. Other regions, such as western Thailand also experienced similar phenomena (Bennett 2013; Kanjanajuntorn 2005).

Most iron artefacts recovered are apparently agricultural or industrial tools (e.g. axes, hoes, knives, sickles, and ploughshares) and weapons (e.g. spearheads, swords, and arrowheads) (Figure 4.1); although, many of them were recovered from funerary contexts. Typologically, forms are associated to specific regions (Figure 4.2) (Bellwood 1997, 298; Venunan 2010). For lower Northeast Thailand, this may suggest, to some extent, the existence of local identity as already seen in other materials such as Phimai black pottery and the preference of rice husk temper in pottery production (see section 3.3.2.2).

Figure 4.1 Iron ploughshares (diagnostic shape), sickles, and hoes from the sites in Upper Mun River Valley

(Images: Higham 2014, 827 (left) and Connelly 2007, 454 (right))

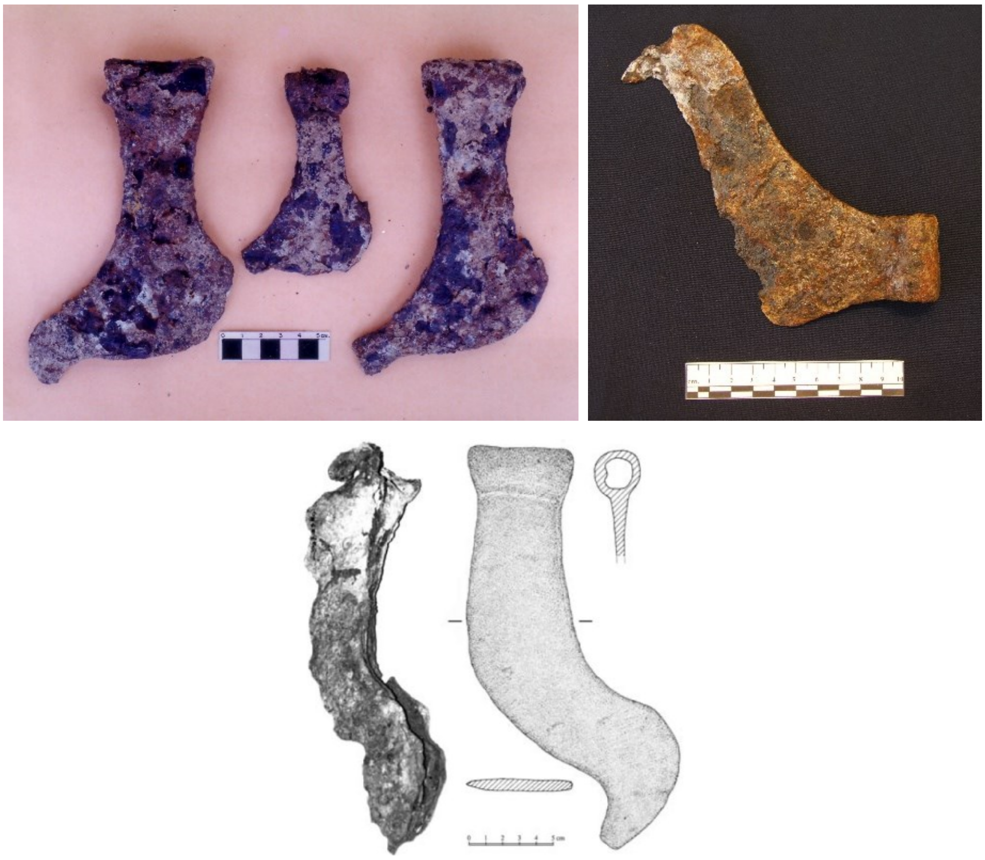


Figure 4.2 Diagnostic shape of iron billhooks found in western (top left), Central (top right), and southern Thailand (below)

(Images: Kanjanajuntorn 2005 (top left), Pryce *et al*. 2006, 299 (below))

4.3.1.1 Production remains

Given the relative abundance of finished objects, production remains are naturally expected. The most abundant find of this sort is slag, which can be found in various quantities and contexts (Figure 4.3). It has been frequently classified only as "ancient slag" or, sometimes, as smelting or smithing slag but without strong supporting evidence. This questionable identification can mislead the following archaeological interpretation, resulting in misrepresentative assumptions (as explained in Cawte and Boyd 2010; Pryce and Natapintu 2009). It should be noted that both smelting and smithing (primary and secondary, and repair) processes produce slag, and that these activities do not have to be carried out at the same place. Therefore, a consideration of some contexts or features has to be done in order to confirm the process involved, as previously argued in section 3.2.

The core of knowledge about early Thai iron production is currently limited to two archaeometallurgically-confirmed sites: 2nd-century-BC Ban Dong Phlong (Nitta 1991) and 6th-14th-century-AD Ban Di Lung (Suchitta 1983) (Figure 4.3 and 4.4).

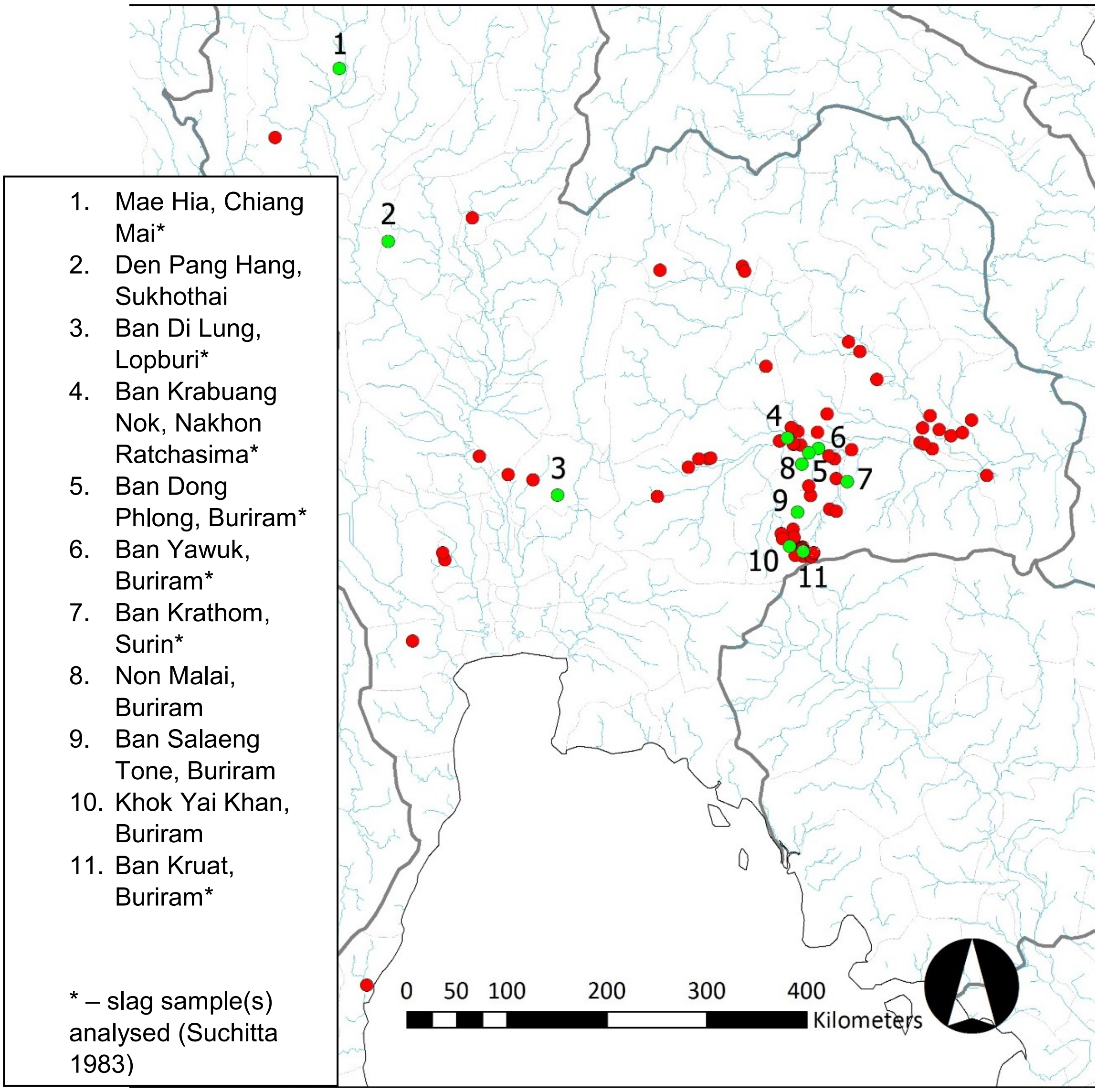


Figure 4.3 Map shows the locations of some archaeological sites associated with slag (red dots) and iron smelting sites (green dots) of different dates. The site distribution is likely to be biased by surveys conducted.

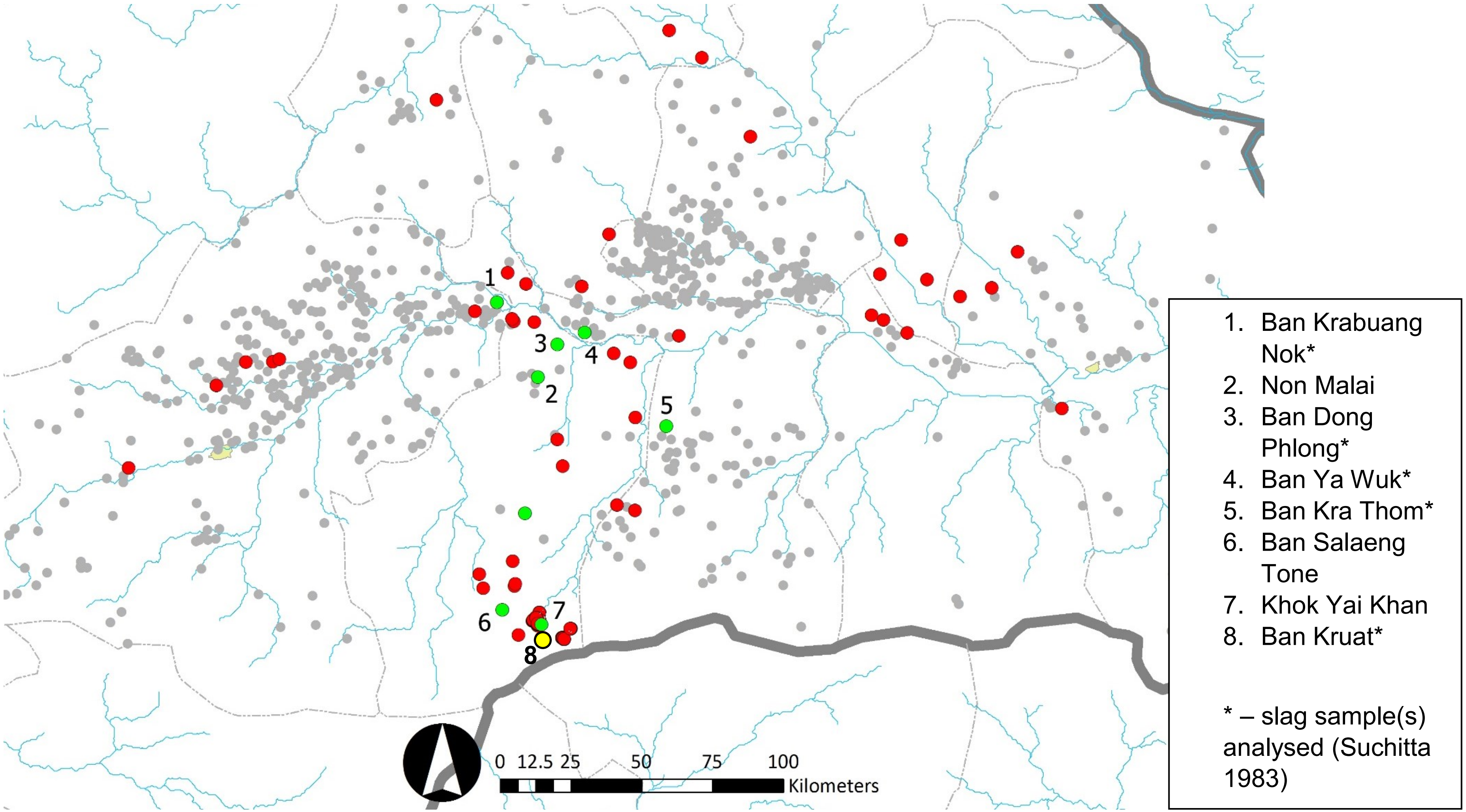


Figure 4.4 Iron Age or early historic sites associated with slag (red dots) and probable iron smelting sites (green dots) amongst Iron Age archaeological sites in lower Northeast Thailand. The yellow dot shows the location of Ban Kruat.

At Ban Dong Phlong in Buriram, 17 shaft furnaces, with and without tapping forehearth and metallurgical waste (e.g. slag and technical ceramics) were found overlaying an early Iron Age cemetery (Nitta 1991, 1997, 156-157) (Figure 4.5). The significance of this site is the discovery of laterite pisoliths in association with the bloomery smelting practice. The presumable relation between smelting slag and laterite ores has posited adaptation of local smelters in exploiting local ores to produce required iron (see section 4.3.3).

Figure 4.5 Furnace remains and a cross section of the furnace at Ban Dong Phlong (below)

(Images: courtesy of Prof Eiji Nitta)

Ban Di Lung in Central Thailand is another smelting workshop, located 25km from Khao Tab Kwai, one of the richest high-grade iron ore deposits in Thailand. The examination of metallurgical remains saw slight differences in the bloomery smelting practice. Slag-tapping shaft furnaces were used to smelt mixed magnetite and haematite ores from nearby sources. Air was suggested to be blown in by piston bellows, which was presumed based on ethnohistoric accounts of ethnic Lawa iron production in Thailand, through tubular tuyères (Suchitta 1983, 181-209).

Accordingly, evidence from both smelting sites indicates that the direct smelting process had been practised during the early periods of iron using in Thailand. However, a technical variability can be seen in the uses of different ores. This is arguably caused by resource availability and environmental constraint. For Ban Dong Phlong, laterite was a probably potential ore the smelters could access in the area being devoid of typical iron ores, whereas the workshops at Ban Di Lung benefited from nearby rich ore sources.

Apart from these two confirmed workshops, other sites with a large quantity of slag have the potential to be smelting workshops, but confirmation is required (Suchitta 1983, 69-72). For lower Northeast Thailand, they include; for instance, Ban Krabuang Nok (Indrawooth *et al*. 1990), Non Malai (Srisuchat 1989, 93) (Figure 4.6), Khok Yai Khan (Jumprom 2005, 186), Ban Kra Thom (Lertlum *et al*. 2010), and Ban Yang (Suchitta 1983, 70) (Figure 4.4).

Figure 4.6 The profiles of the slag mound at Non Malai, Buriram

(Images: courtesy of Assoc Prof Surapol Natapintu)

Concerning object forging activity, evidence is drawn from the Upper Mun River Valley and Upper Thai-Malay Peninsula. The activity was indicated by the presence of iron objects and SHBs. At sites like Noen U-Loke (Higham 2011b, 135), Non Ban Jak (Higham *et al*. 2014, 10), Khao Sek (Pryce 2015 pers.comm. 16 July), and Khao Sam Kaeo (Biggs *et al*. 2013; Pryce *et al*. 2006, 296-300) (Figure 3.7 and 3.8), this kind of slag was found in a domestic or industrial context and concentrated at one location or on a floor possibly suggesting the remnants of workshops.

It is worth mentioning evidence in Cambodia as these two areas shared a close relationship. Metallurgical evidence is still very scarce. Primary production is represented by 13 slag concentrations found at Chep-Mlu Prey in Preah Vihear (Thuy 2010). According to the report, the slag was likely tapped (Figure 4.7), while the tuyères were of tubular type (Thuy 2010, 56). There is also evidence of a tight cluster of slag deposits, which might be a result of large-scale intensive production or successive activity. The smithing evidence is seen at the Iron Age cemetery of Prohear where SHBs were found along with other industrial remains (Reineke *et al*. 2009, 63-64) similar to the Thai cases aforementioned.

Figure 4.7 Slag from Toul Reousey Trib

(Image: Thuy 2010, 33)

4.3.2 Iron in the Angkorian period (9th-13th/14th century AD)

In this succeeding period, archaeological evidence is complemented by epigraphic evidence, which may add another dimension to contextualise the regional history of iron.

Recent archaeometallurgical studies on primary production remains, especially in Cambodia, also shed light on this topic.

The social importance of iron cannot be recognised at the moment of its appearance only. For Angkor, iron was probably recognised as a strategic metal. Its uses ranged from day-to-day utilitarian implements to military weapons and armour (Jacq-Hergoualc'h 1979; Nafilyan 1967 in Hendrickson *et al.* 2013) (Figure 4.8). Rice farming and civic construction projects, which were imperial economic foci, possibly demanded most of the iron supply for tool production, including diagnostic architectural crampons (Demaçay and Royère 2001; Hendrickson *et al*. 2013) (Figure 4.9). The importance of iron in the Angkorian period is therefore apparent; although, the actual quantity is unknown. In contrast, epigraphically, iron seems to be the most conspicuously absent metal, compared to other metals. It is striking that iron is near absent from a list of donated items, and very few inscriptions refer to it. Of them, the inscription at Preah Khan infers iron being donated in large quantity by the king and followers to temples across the empire (Diskul 1966, 58). This suggests that iron, while important, might have been recognised differently for its socioeconomic role or value.

Figure 4.8 Bas reliefs of Angkor Wat showing the scenes of Angkorian army carrying weapons

(Images: Groslier 2002, cover, 34)

Figure 4.9 Iron crampons used for joining two stones together. Note the iron tools were also found as shown in the top left corner of the bottom image.

(Top image: Thamrungraeng 2005, 49)

4.3.2.1 Iron production in the Angkorian contexts

As per other metals in this period, iron has been better understood as finished artefacts. Its early life (primary and secondary production) has been revealed mainly by archaeology, though still very limited. Only a handful of contemporary produciton sites have hitherto been known. The most informative source of iron industry is currently from Preah Khan of Kompong Svay (hereafter “PKKS”) and Phnom Dek (Iron Mountain) in Preah Vihear, Cambodia studied by the “Industries of Angkor Project (INDAP)” (Hendrickson *et al.* 2010, 2012, 2013; Pryce *et al*. 2014). It should be noted that Ban Kruat is arguably the best candidate for smelting locales in the Angkorian period currently known on the Thai side of the border (Figure 4.10).

Figure 4.10 Map shows the locations of Angkor and currently known Angkorian iron production locales.

PKKS is located approximately 95km east of Angkor and is a 10th-13th-century-AD 22km^2 urban/ritual complex, the largest ever built by the Angkorian Khmer (Hendrickson *et al*. 2013, 32-33) (Figure 4.11). The site size, the succession of construction, and the presence of a direct road connecting PKKS to Angkor suggest the importance of this complex to the empire. The construction of PKKS may have been crucial to Angkor’s political stability. PKKS was situated on the eastern frontier where the intense conflicts with Champa and *Đại Việt* took place (Hendrickson 2011). This complex could arguably serve as an observational outpost. However, the key role of this complex may have been a producer of iron to Angkor. This is explained by the presence of three main large iron slag concentrations inside the enclosure (Hendrickson *et al*. 2012; Hendrickson and Evans 2015) (Figure 4.11); although, these remains belong to the mid-13th-late 17th

century AD post-dating the last construction (Hendrickson *et al*. 2013; Hall *et al*. 2016, 61). Accordingly, the operation may have been activity during the period when power was shifting away from Angkor (Hendrickson *et al*. 2013, 43). Furthermore, PKKS stands in proximity of Phnom Dek, the richest reserves of high-grade iron ores in Cambodia giving a good access to the deposits. In addition, the surrounding areas of this mountain has been the home of iron-Kuays, who operated intensive iron production activities in the mid-20th century AD (Figure 4.12). It has been hypothesised that their ancestors were important suppliers of iron to Angkor in return for other goods, tax exemption, and/or political recognition (Dupaigne 1992; Jacques and Lafond 2007, Chapter 5; Pryce *et al*. 2014; Vickery 1998, 317). Two metallurgical sites, dated to the 9th-11th and 19th-20th century AD, were recently identified and excavated near Phnom Dek (Pryce *et al*. 2014, 147, 150).

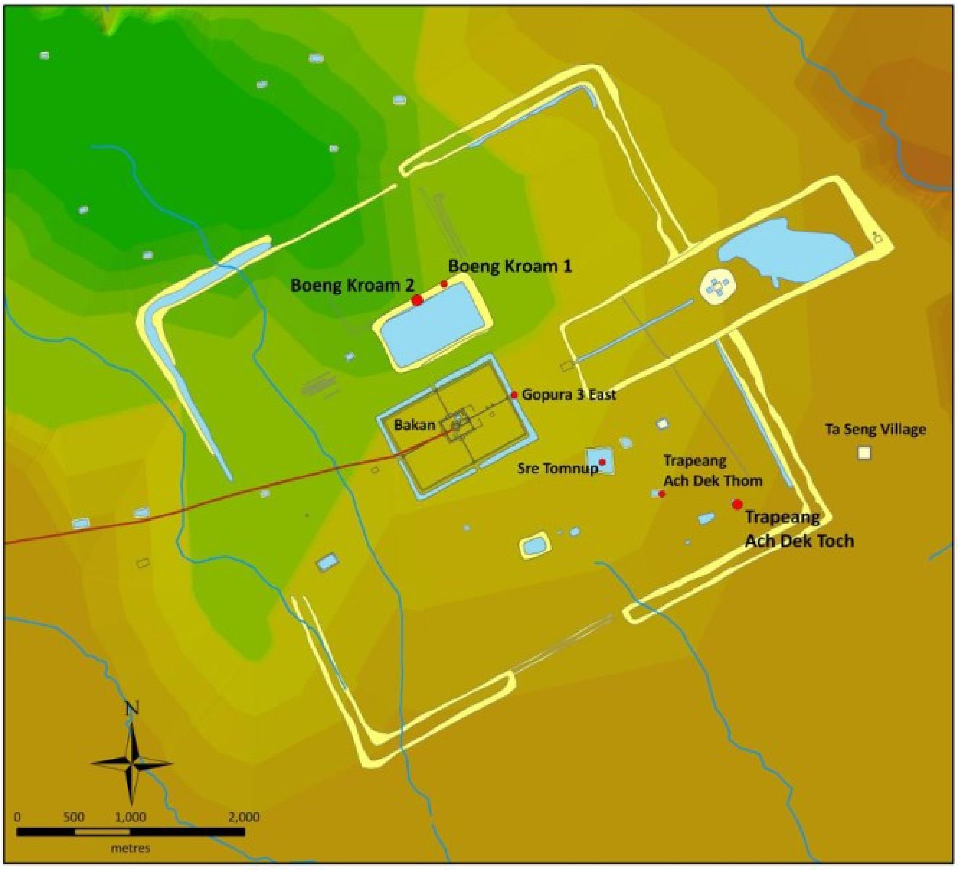


Figure 4.11 Plan of Preah Khan of Kompong Svay complex with slag concentrations (red dots)

(Image: Hendrickson *et al*. 2012, 4)

Figure 4.12 Engraving depicting the Kuay iron foundry in the 19th century AD

(Image: Boulanger 1887)

Archaeometallurgical studies have revealed historical and technological trends of iron production from the pre-Angkorian to recent historic periods, though with substantial chronological gaps. The results indicate bloomery smelting practice may have evolved in response to socio-economic changes. In the early phase, based on evidence at Phnom Dek, a low-efficiency and low-productivity smelting operation in natural draft furnaces using large-bore tuyères was employed. This operation may have been favoured as it helped to overcome the competition for labour with other sectors (e.g. agriculture) and better answer to local markets that preferred soft iron rather than steel (Pryce *et al*. 2014, 159-160). The subsequent change occurred during the period when PKKS participated in producing iron. The forced-draft smelting furnaces, as suggested by smaller-bore tuyères, were in operation in order to better respond to an increase of demand for iron in the terminal period. This suggests that the production may have become more intensified and tightly controlled. It is not clear whether PKKS still maintained its role in iron production or was simply abandoned (Pryce *et al*. 2014, 160, 162).

Figure 4.13 Relatively small-bore tuyères from Boeng Kroam (left) and Trapeang Ang Dek (right)

(Images: Hendrickson *et al*. 2010, 18 (left) and 2012, 9 (right))

Further information about Angkorian iron industry is revealed by evidence at Khvav village located in between Angkor and PKKS (Figure 4.10). The excavation at one of the five slag mounds saw a comparable set of metallurgical remains to PKKS including poorly preserved furnace structures, tubular tuyères, tapped slag, and high-grade oxide ore fragments. In addition, holes for wooden pole thought to have been for a shelter covering the workshop were also identified (Im 2011, 2).

In summary, according to Angkorian evidence from Cambodia, the technology was dominated by the direct smelting method. No traces of cast iron technology have been found, despite a strong Chinese influence in the ceramic production. Local high-grade iron ores, also probably mixed with low-grade ores, were sourced from the location near the smelting sites, such as Phnom Dek. The importance of the production might be high as suggested by the relationship between PKKS and Phnom Dek. PKKS was possibly established to control the flow of supply to Angkor, whereas Phnom Dek might be a centre of the production. In addition, smaller production locale, such as Khvav might serve as a producer for nearby settlements. However, the question remains for the production and organisation in the peripheral area, such as Ban Kruat, to what extent the technology and administration could be comparable to what seen in the Angkor area.

4.3.3 Ethnohistorical evidence of iron production in Thailand

First-hand ethnographic information (e.g. eyewitness and interview) is a potentially useful approach in understanding pre-industrial production. Information gained could cover aspects that excavation and laboratory work find difficult to provide such as economic and social parameters such as labour and raw material cost, rationales and beliefs embedded in actions, and effects of the production on society. Ethno-archaeometallurgical work in Africa illustrates best the potentials of such information (e.g. Barndon 2004; David and Kramer 2001, 328-355; Humphris 2010; Iles, 2011; Killick 1990; Kusimba, 1993; Schmidt 1996, 1997). Nonetheless, some information such as eyewitness descriptions may need to be used with caution as not all informants and recorders have good understandings of process of interest. In addition, there is the risk of anachronistically transposing ideas from the present to the more distant past.

There have been very few studies focusing on pre-industrial iron production in Thailand, and published data are mostly related to iron forging rather than smelting. This bias may be due to the fact that there are local traditional blacksmiths in many villages who produce iron objects. This is in contrast to indigenous iron smelting which has gradually been abandoned or substantially changed due to being uneconomical after introduction of foreign ferrous technology, especially European (Bronson 1985; Bronson and Charoenwongsa 1994, 5-6). The subject also may not be in focus of scholars for documentation. Only three ethnographic cases of direct iron smelting have so far been reported from late 19th and early 20th century AD explorers' accounts in Loei (Northeast Thailand) and Chiang Mai (northern Thailand) (Bronson and Charoenwongsa 1994). The Chiang Mai case (Ban Bo Laung) has since been revisited for many times (e.g. 1981

(Suchitta 1983) and 2012 (Tintip 2012)) generating better descriptions for both technical and social aspects of the activity.

As details of each description can be found in the publications cited, this review will focus on some points relevant for this research. The Loei accounts offer the data on the activities carried out at two different villages – one in 1860s and the other in 1910 (Bronson and Charoenwongsa 1994, 8, 11-12). Magnetite (1860s) or haematite ore (1910) was procured from mines. The distance was about 5 km from the village for the 1910 case. The ore was then either immediately smelted near the mine (1860s) or brought to the village to be smelted (1910). The types of furnaces were described rather vaguely, either as "holes about a yard and a half square hollowed out" (1860s) or a furnace of approximately one-half metre high (1910). In the 1860s case, the raw bloom was then forged into tools in a hearth connected to a pair of upright piston bellows operated by kids. The account further stated that the same ironworkers were responsible for the whole process and did not work full-time (agriculturalists-artisans). It is known from the 1910 case that smelting was already abandoned, and raw iron was imported to the village by Chinese merchants to be forged.

More details can be drawn from the ethnographic studies at Ban Bo Luang (see Suchitta 1983). This village has been home to Lawas, an ethnic group speaking a Mon-Khmer language. Magnetite may have again been extracted which was procured from the deposit 35 km from the village. The ore, transported by elephants or women and men, was smelted at the village for there was no flat ground near the mine. The clay-covered bamboo-framed furnace had a cubical shape with a height of 70-100 cm. The structure had three openings. The first hole (10-20 cm in diameter) was in the top, while the second one was smaller (5 cm in diameter) and used for inserting a tuyère. The third one with 10-15 cm in diameter was probably used for extracting the bloom and tapping slag. This could be closed when air was blown into the furnace through two double-acting piston bellows.

The charge comprised ore, charcoal (*Castanopsis* spp. and *Dipterocarpus tuberculatus* Roxb.), and small pieces of slag from previous smelts. However, the proportions of the charge components are not recorded. Possible information about iron bloom was revealed by a preserved bloom kept by the informant. It was analysed and found to be mild steel of 0.28% carbon mixed with slag weighed around 0.94 kg. The bloom was then forged in the same furnace into implements.

In the present day, only forging is carried out in the village by using scrap iron (e.g. iron bars from old cars) (Tinthip 2012, 98), while smelting has been abandoned completely. This activity is done in a small workshop in the backyard of each blacksmith who can produce around 5 tools per day. Modern tools such as grinder are used to assist the ironworking process, but no power hammer are employed. The products are used in the households of the blacksmiths and sold to nearby communities.

Social aspects of the activity can also be learnt from these studies. The ironworkers again were not full-time, and their objects were traded to the Chiang Mai area. Iron was also once used as a dowry to the husband at marriage. There was no strong indication of gender separation in the activity as both sexes participated in it. While a feast used to be held annually (Tinthip 2012, 115) to pay a respect and celebrate five spirits of iron ore deposits, today local ironworkers do not smelt iron anymore, and hence the feast takes place only every five years. This is to ensure a good outcome of the activity. This same celebration of local spirits affiliated to ironworking activity is commonly practised among local blacksmiths in Thailand.

As mentioned earlier, ethnographic evidence for iron production in Thailand is very limited, but it does provide some very interesting insights into the social aspects of this activity in addition to information about furnaces and air bellows. This is an issue that is difficult to find archaeologically and could be taken into account when reconstructing Ban Kruat production in Chapters 8 and 9. Unfortunately, there is no known ethnographic evidence for the use of laterite smelting, which means that there is not only temporal distance between the ethnographic accounts and the archaeological record investigated here.

4.3.4 Laterite smelting as an alternative practice in Thailand?: some notes from archaeological evidence

As the previous chapters already introduced, the model was adopted in light of geological scarcity of typical iron ores in Northeast Thailand in spite of large quantities of iron artefacts recovered (e.g. Bronson 1992, 66; Higham 1977, 110; Indrawooth *et al*. 1990, 94; Moore 1988, 125; Nitta 1991; Tantisukrit 1983 in Indrawooth *et al*. 1990; Welch and McNeill 1991, 225). However, this model, though has been proved elsewhere ethnographically and archaeometallurgically (see section 4.3.3.2), has also been questionable for their applicability to all smelting evidence in this region. The issues are discussed in detail in the dedicated section, and this thesis throws in more data in hope to clarify it, but it is first to outline relevant information about laterite and the archaeological implications given by previous studies.

4.3.4.1 Laterite ores

For laterite, in general, in the tropical regions, including sub-Saharan Africa and Southeast Asia, a repetition of wet and dry cycles facilitates the leaching of certain elements (i.e. iron, nickel, and aluminium) to be washed out from weathered parent rocks and deposited with soil or clay material to form laterites, and this process is known "laterisation" (Aleva *et al.* 1994; Kearey 2001; Seeley 2000, 33). This material is often characterised as reddish-brown structureless sediments or as nodules within sediments. It can contain aforementioned minerals, including others, such as kaolinite, chromite, zircon, and titanium. A change in its structure from soft and workable to rock-like solid is probably best recognised, and laterite has been used construction material since ancient times, including in the Angkorian period.

Laterite can contain various oxides and oxyhydroxides of varying compositions, potentially turning into an ore for a variety of metals. The current use of laterite in modern metal industries is as sources for nickel (nickeliferous laterite) and aluminium (laterite bauxites) (Pohl 2011, 83, 226; Robb 2005, 227; Thorne 2011, 5-7). Iron can also be extracted from it, but of lesser in importance (Pohl 2011, 81). This exploitation typically aims for a ferruginous residual zone, which consists of the remnants of oxide (haematite) and oxyhydroxide ores (limonite and goethite) (Pohl 2011, 81; Rostoker and Bronson 1990, 43). These oxides/oxyhydroxides can concentrate to become oolithic or pisolith. Though it contains iron, its contents can vary massively between 1-60 wt% (Aleva 1994, 6; Seeley 2000, 33), and only those with high iron content are suitable for direct iron smelting.

4.3.4.2 Laterite iron smelting in archaeology and ethnoarchaeology: a different smelting practice

Though being of lesser importance in modern iron industry, laterite was valuable for ancient iron production. Abundant archaeological and ethnoarchaeological evidence from sub-Sahara Africa (e.g. Chami 1999, 8; Chirikure 2005; Darling 2009, 105; Gordon and Killick 1993, 259; Hillman and Hillman 2010, 118; Humphris 2010; Iles 2011, 347, 412; Lyaya 2012; 16; Killick 2013 in Killick 2014; Togola 1993, 53; van der Merwe and Avery 1987, 155) and Greece (Photos 1987, 1989) has demonstrated a relation between laterite and iron smelting. A possibility of laterite being smelted was frequently proposed due to the presence of the laterite deposits close to the sites (Chami 1999, 8; Darling 2009, 105; Hatton 1967 in Chirikure 2005, 119; Togola 1993, 53). In some instances, laterite ore samples, both geological and archaeological (i.e. associated with smelting context) were studied archaeometallurgically in which the natural variability of this material was shown. The level of iron oxides available for the reduction appears to be diverse, but mostly lower than 60 wt% FeO. Some accompanying components, such as aluminium, titanium, manganese, and nickel oxides could fluctuate from archaeological site to site. A high level of alumina (>7-8 wt%) in slag chemistries was frequently documented (Chirikure 2005, 289; Lyaya 2012, 205). Use of MnO-rich (Iles 2011, 347, 412, 2014) or NiO-rich laterite (Photos 1987, 1989) has sometimes been documented too, resulting in high levels of these particular oxides in the slag.

Combined ethnography and archaeometallurgy may be the best approach in shedding light into how laterites were processed. The cases from Chulu (van der Merwe and Avery 1987, 155) and Kasungu in Malawi (Gordon and Killick 1993, 262) and Zande in Sudan (Hillman and Hillman 2010, 118) agreed that iron oxide concentrates in the forms of 'pellets' (Chulu) or 'pisoliths' (Kasunga and Zande) were preferred. This may have been due to its concentration and changeable structure when beneficiated. Since these ores mainly contain iron oxyhydroxides, when they lose water they can become more porous, which allows a better and quicker interaction between carbon monoxide and oxides during smelting (Killick and Miller 2014, 250; Rostoker and Bronson 1990, 52). A higher-resolution explanation derived from the metallurgical examination of Kasunga laterite pisoliths. It showed that the good nodules contained pure hydrated iron oxide interspersed with large quartz grains and kaolin with low Fe content of 20-30% (Killick and Gordon 1989, 120). The metalworkers smelted this ore in the low-temperature and low-reducing zone in a shaft furnace operated by natural draft alone (Gordon and Killick 1993). Though the iron oxides might seem at first insufficient for smelting, a bloom was successfully retrieved through a reduction of the iron oxide nodules presenting between gangue. Avoiding ores with small quartz grains was essential as they would combine with iron oxides to form slag leaving less iron oxides to be reduced into iron metal. With larger grains present, iron oxides can be reduced and consolidate before slag was formed and drained out of the iron shells (Gordon and Killick 1993, 259-263) (Figure 4.14). Noticeably, iron oxide would never be dissolved but directly reduced successively into magnetite, wüstite, and metallic iron (Killick and Gordon 1989, 120, 121). Iron created then formed a coherent unit (bloom) under influence of gravity (Gordon and Killick 1993, 262; Killick and Gordon 1989). Fuel consumption and final product were also observed. The fuel:ore used was 19.4:1 significantly higher compared to 5:1 in forced-draft bloomery production (Gordon and Killick 1993, 261). After 90 hours of smelting of 165 pounds of ore arrived a final product was approximately 70-80 pounds of bloom with variable carbon contents (e.g. 0.8% C steel was also documented) due to a high fuel:ore ratio (Gordon and Killick 1993, 264). It should be noted that this study seems to be only analysis-based explanation for the mechanism as to how one can smelt iron out of laterite. This thesis hoped to offer another example into the picture.

Figure 4.14 A micrograph of the slag sample shows the nodule of iron mineral from laterite soil reduced to iron

(Image: Gordon and Killick 1993, 263)

4.3.4.3 Prior studies on laterite iron smelting in Thai archaeology

Information concerning the use of laterite in iron smelting is very sparse as only three smelting sites do yield direct evidence of laterite associated with smelting remains. They include Ban Dong Phlong (Nitta 1991, 1996, 1997), Ban Khao Din Tai (Yoopom 2010, Venunan 2011), and Ban Sai Tho7 (Lertlum *et al*. 2010); however, only laterite samples from the first two sites have been examined, and only to a limited extent.

At Ban Dong Phlong, the analysis of laterite nodules showed that their structure was a band of iron oxide in a groundmass of quartz or clay material (Figure 4.15), similar to what Gordon and Killick (1993) described. One sample contained approximately 60 wt% FeO, 30 wt% SiO_2, and a considerable level of Al_2O_3 (8 wt%). This interestingly matched chemically the slag chemistry which had alumina around 9-12 wt% (Nitta 1996, 48).

Figure 4.15 Iron nodules from Ban Dong Phlong. Note that only outer shell is likely to be rich in iron oxides, whereas the core is mainly quartz or clay-like material.

(Image: courtesy of Prof Eiji Nitta)

For Ban Kruat, Pryce and Natapintu (2009) were the first to tackle the issue. They assessed two archaeological samples which the interpretative result was still inconclusive, probably due to the number and suitability of the samples analysed and the unavailability of slag for the analysis. However, it did characterise local laterite as being different from that at Ban Dong Phlong in that Al_2O_3 was considerably high (8-11 wt%), but FeO was significantly less than 47 wt% (Pryce and Natapintu 2009, 255). Venunan (2011) later examined 11 slag samples and one archaeological laterite together in order to address the concerned issue (Figure 4.16). The result showed a higher level of FeO at 53 wt% and again significantly high Al_2O_3 (11 wt%) (Venunan 2011, 68), which was arguably in good agreement with the high alumina content in the slag (11-14 wt%). Accordingly, the author suggested laterite as a highly likely ore.

Figure 4.16 Laterite fragments archaeologically recovered at Ban Khao Din Tai

Cawte and Boyd (2010) compared chemically three forms of laterite (pisoliths, laterite block, possibly in antiquity, and a modern laterite brick) to determine the likelihood of their suitability for smelting. The samples were divided into various groups of those in a natural state and those beneficiated (crushed, washed, and/or roasted) (Figure 4.17). The study could not conclude to what extent the laterite could be smelted but confirmed a chemical variability (21-56 wt% Fe_2O_3 and 4-20 wt% Al_2O_3) (Cawte and Boyd 2010, 637).

Figure 4.17 Iron nodules from Ban Muang Kao

(Image: Cawte and Boyd 2010, 633)

In summary, the model of the laterite being smelted in Northeast Thailand has been built upon regional availability of laterite. This have led some scholars to speculate that direct iron production in the Khorat Plateau was based on the use of laterite as an ore (Nitta 1996, 61). Although the use of laterite in such smelting has been attested elsewhere by ethnographic and archaeometallurgical studies, the applicability of this model for Thai context has been questionable in that, apart from Ban Kruat (Pryce and Natapintu 2009; Venunan 2011; Yoopom 2010), only Ban Dong Phlong yields direct evidence for the use of laterite in smelting (Nitta 1991, 1996, 1997). Previous assessments of the use of laterite in direct iron smelting appear to raise more questions, and no detailed studies have been dedicated to understand the technical mechanisms of and constraints behind local laterite smelting. Moreover, looking at lower Northeast Thai archaeology, there is also a possibility that typical iron ores might have been imported to the region through active trading networks.

Nonetheless, the previous studies still contribute greatly to this thesis for they characterised the ore samples from different places. The preference of concretions in smelting conforms to the cases reported in the sub-Saharan countries. High alumina contents (8-14 wt%) appear to be diagnostic of laterite in this region and correspond to the high alumina levels found in the slag samples. This may suggest the smelting of high-alumina-containing laterite, but the alumina contribution of degraded technical ceramics to the slag also needs to be assessed.

The review of previous studies also points out some issues that need to be clarified for smelting in Ban Kruat and Southeast Asia more generally. They concern detailed identification of structure and mineralogy, and the associated smelting parameters of temperature and redox. The assessment of reducing mechanism as proposed by Killick and Gordon (1989) will be done to demonstrate to what extent this may be the case for Ban Kruat. The productivity of the smelting using this type of ore needs to be examined.

4.3.5 Proposing hypothetical models for iron production within archaeological framework of lower Northeast Thailand

As evidence for the production and use of iron in Thailand has been reviewed, it is discussed in conjunction with the chronological frameworks in Chapter 3 in hope to propose a preliminary model for organisation of iron production during the 5th century BC-14th century AD; although, the available evidence for regional iron production and consumption is sparse, as shown above. The degree to which this hypothetical model is applicable for Ban Kruat iron production will be evaluated through the interpretation of archaeological and technical data (Chapters 7-8).

4.3.5.1 Iron production prior to Angkor

From archaeological evidence, iron appears to have been easily accessible by local consumers. However, unlike exotic goods that were imported from external sources, iron was possibly not part of long-distance exchange networks, but rather it was locally produced, probably as community-based production, particularly forging and repair of objects, and finished objects may have been circulated locally (Bellwood 1997, 286;

Welch 1989, 19-20). Nonetheless, market preferences for different qualities of raw iron and final products need to be considered too. The presence of ploughshares and small formal variation of iron tools amongst sites is suggestive for the objects being of local tradition and for regional use. A high volume of ironworking sites, judging by the presence of smithing slag, in the region may indicate the localisation of iron metal and objects, and secondary production might be a common activity in which the local population participated. However, considering the nature of extractive metallurgical operations, requiring a confluence of raw materials and skills, the majority of sites with slag may in fact be related to secondary production (Pryce and Natapintu 2009), while primary production only took place at restricted locations in which not all communities participated, likewise the production of copper/bronze and Phimai black wares. It is true that metallurgical identification of all concerned sites is required to address this observation. To date, less than 10 sites have the potential to be primary production workshops (Figure 4.4), as suggested by considerable quantity of slag, with some sites accompanied by preliminary chemical examination of slag (Suchitta 1983, 75). The morphology of these sites is fairly comparable in that they are large mounds full of metallurgical remains along with domestic finds (e.g. sherds).

Following this observation, primary iron production may be counted as specialised production, restricted to particular communities. These workshops possibly served as foci for the redistribution of iron amongst nearby settlements, possibly as marketplace (Welch 1989, 22). Scale of production could have been on large scale in order to meet demands from various settlements. However, this is likely to be based on rough estimation of accumulated layers of metallurgical waste found at some contemporary smelting sites, such as Ban Dong Phlong, Non Malai, and Ban Krabuang Nok (Nitta 1996). Increase in demand for iron stimulated by the growth in population size and agricultural intensification may have encouraged more producers to participate in the activity (Higham 1989, 219; Welch 1989, 20, 22; Welch and McNeill 1991, 224). Evidence at Ban Krabuang Nok, Non Malai, and Ban Dong Phlong suggests that metallurgical activities, to some extent, replaced earlier use of the site as cemetery (i.e. metallurgical evidence superimposes cemetery layers). New specialised smelting workshops might have been established to focus on producing iron (Higham 1989, 218-219; Welch 1998, 216). This may have involved the expansion of the existing communities to occupy new lands, and in this process, smelters and blacksmiths may have travelled and established new workshops in settlements. However, more evidence is needed to clarify this supposition. In addition, secondary production of iron objects (e.g. forging and repair) could have been carried out more widely on habitation sites and on community scale.

Regionalisation of craft production is evidently indicated by a shared Phimai black pottery making tradition which many local potters followed. Although multiple workshops produced the wares using local clays, similar wares were circulated across the region. The picture for iron production in lower Northeast Thailand is still quite a blur. The presence of some regionally diagnostic types of iron objects (e.g. ploughshares) may exhibit a regional preference of local markets and consumers that blacksmiths had to take in account. In terms of technological communication amongst smelters and blacksmiths, it is still not clear since comparative studies of iron production remains and objects have rarely been done, but some scholars (e.g. Bellwood 1997, 286) have suggested that knowledge of its smelting and forging might spread easily due to the superior economic potential and availability of this metal. The technological cross-comparison of Ban Kruat iron technologies and others might shed some light on to what extent technology might display an existence of regionalisation of iron production.

Socioeconomically, the relations between iron and lower Northeast Thai societies has long been emphasised by many scholars (Higham 1989, 234-235; Higham and Thosarat 2012, 167; Nitta 1996; Welch 1989, 1998). As suggested by the probable functions of iron objects, they were widely used in agriculture, construction of moats and water channels, and warfare. The first two activities were considered crucial economic sectors during the Iron Age (see section 3.3.2). The potency of iron was possibly given by its superior properties. When treated properly, iron is transformed into steel (0.3-2% C) gaining more durability and tensile strength, compared to bronze and woods. Iron was rapidly exploited as implements, replacing bronze, which was used widely as ornaments in the Iron Age. Moreover, iron ores (e.g. laterite and limited local sources of typical iron ores) are more widespread than are sources of copper, tin, and lead. Raw iron billets may have been imported through exchange networks, but this has to be proved. Forging and repair of iron objects may have been carried out at many settlements as suggested by a widespread of probable smithing slag across the Iron Age landscape (Figure 4.4). On the contrary, smelting may have been confined to some able settlements. Accordingly, it has been proposed that some elites may have involved in controlling organisation of production in order to strengthen their economy and indirectly acquire wealth from it (Higham 1989, 236; Nitta 1996, 61; Welch 1989, 22; cf. O'Reilly 2014, 302).

To test this model against Ban Kruat iron production, the technological tradition of Ban Kruat ironmaking needs to be characterised. The information obtained will verify the use of laterite as an ore and suggest possible mechanism of how laterite was smelted. Remnants of unreacted laterite ore in slag and high-alumina-containing slag influenced by the use of alumina-rich laterite can be a good indicator. The evaluation of the degree of standardisation and variation amongst mounds would facilitate an examination of social components of production (e.g. specialisation, control of production, and efficiency) (Costin 2001, 2005; Humphris 2010; Iles 2011). Determining technical variability across the production landscape of Ban Kruat, it helps address to what extent the smelting workshops in Ban Kruat might share similar technical traditions. If so, technical variation of smelting technologies across Ban Kruat would be expected to be low due to similar recipe followed (top-down standardisation), but geological constraints from the smelting of laterite has to be taken into account as it could have technically forced the smelting practice to be similar.

The local and regional archaeological framework, when integrated with the technical information, is hoped to explain the development and place of Ban Kruat iron production in regional archaeological and ferrous archaeometallurgical settings during these periods. To what extent Ban Kruat iron smelting technologies can be compared to other known traditions (e.g. Ban Dong Phlong, Ban Di Lung, and Phnom Dek traditions) and what could be potential factors or influences associated are hoped to be addressed by newly generated data from Ban Kruat.

4.3.5.2 Iron production in the Angkorian period

As Chapter 3 demonstrated, temple networks and commercial activity driven by merchants and marketplaces may have been mechanisms behind the production and circulation of goods in the empire. With flexible administration in order to balance power between the king and elites, the Khmer economy may have been both tightly controlled for some sectors and flexible for others (mixed economy) (White 1995, 114). Taking this observation into consideration, scenarios for how iron production in Ban Kruat was organised are proposed below.

The first scenario is that production was centrally controlled by a local temple or administrative centre. This is plausible if one considers the irrigation technology introduced by Khmer culture along with the introduction of other social and ritual ideologies. Accordingly, controlled iron technology or recipes (e.g. similar smelting practices across Angkorian territories) might have been employed here. Furthermore,

more workers might have been brought in by higher-ranking administrative centres (e.g. Muang Tam, Phimai, or Angkor) to increase output; although, it may also lower productivity if new workers introduced were unskilled. This extra group of labourers might have been part of an endowment which might have worked under the supervision of head smelters. Finally, iron product was possibly sent hierarchically to larger settlements and Angkor in return of other goods, protection and recognition. However, the majority of supply may have been circulated among the western territory rather than sent all to Angkor, as suggested by the ceramic products of Ban Kruat (see section 3.3.4.2.3) Local settlements might have supported production activities, especially feeding iron workers.

The second scenario is that temple only demanded the product but did not actively interfere substantially with the underlying production technologies and organisation. The smelters and associated labourers would be local rather than foreign ones. Without the direct central control from Angkor, high technical variation between regions (e.g. Ban Kruat and PKKS) might be expected. However, the geological constraints are again needed to be testified to which extent they may affect the local smelting technology. The distribution of iron production would have been similar to the first scenario. This would well display the possibility that Angkor might have administered the peripheral areas differently from the core zone, possibly as Lustig (2009) and Pryce *et al*. (2014) suggested. Moreover, this scenario may be supported when considering that lower Northeast Thailand was once a stronghold of one of ruling royal families, thus, the production at Ban Kruat may have been of local to this region, and the organisation of production might be subject to local administration not totally by Angkor.

To assess these scenarios, the characterisation of Angkorian iron technology at Ban Kruat needs to be done in comparison with the Iron Age practice to what extent they are similar or different. Then, technological comparison between Cambodian sites and Ban Kruat will infer the degree of variation in Angkorian iron technology. Thus, if the technical diversity can be detected, it should also help differentiate the groups of smelters or smelting technologies. Integrating the technical information into the archaeology of Angkor will better illuminate how the iron production in Ban Kruat might have been organised in comparison to iron industry in Angkorian heartland.

Chapter 5 Applied methodology: Fieldwork and archaeometric analytical methodology

Acquiring relevant technical data was an essential step of this thesis in order to address research questions concerning local iron technologies in Ban Kruat. A suitable methodology was formulated to ensure the successful generation of a reliable dataset, which would be as far as possible comparable with earlier studies (Chuenpee *et al*. 2014; Venunan 2011; Yoopom 2010). This methodology involved consecutive stages starting with fieldwork to revisit and assess local slag deposits in order to understand the nature of the sites. This allowed sites and samples suitable for archaeometallurgical analysis to be selected – while acknowledging a degree of uncertainty as to how representative samples are of a reference population (Humphris *et al*. 2009). These samples were then subjected to archaeometric analysis, to acquire macro- and microscopic and chemical information, relevant for the technological reconstruction. The newly generated data were evaluated in conjunction with the interpretative (Chapters 2 and 4) and chronological framework (Chapters 3 and 6), facilitating discussion of the role and organisation of iron production and its relationship with the broader natural, political, and socioeconomic environments of lower Northeast Thailand.

The methodology chosen was founded upon my previous experience with metallurgical remains in Ban Kruat, particularly at KDT2 and STH8 (Venunan 2011) and considering the limitations of access to analytical equipment, budget, and time frame available. While this methodology was suitable for a study of technological practice and variability, it is not suitable for other questions, such as provenance of ores and clay sources and the relationship between production sites and consumers.

5.1 Fieldwork and sampling strategy

5.1.1 Fieldwork in 2012

Since this research attempts to elucidate broad technological traditions of iron production on the Ban Kruat landscape, it was essential that a large geographical area should be taken into account in order to understand the nature of metallurgical remains and the relationships between production activity and local natural and social environments.

Previous archaeological surveys in Ban Kruat, in the 1980s (Chaikulchit 1997; Nitta 1991, 1997; Prommanoj 1989) and in 2005-2007 (Chaiya 2007; Lertlum *et al*. 2008; Sampaongern 2005-2006) have provided references to ferrous metallurgical remains in

Ban Kruat. Of these, the 2005-2007 survey generated the majority of archaeological data for ancient iron production in Ban Kruat. Sixty seven slag deposits grouped in nine clusters were mapped through the course of these unsystematic surface surveys (Lertlum *et al*. 2008, 47) (Figure 5.1). The subsequent archaeological studies on two mounds (KDT2 and STH8) revealed some initial technological information (Chuenpee *et al*. 2014; Venunan 2011; Yoopom 2010). Detailed discussion of previous studies will be presented in Chapter 7.

While the project provided precious information, knowledge prior to this research was largely restricted to two excavated sites (KDT2 and STH7 – see Chapter 7 for information) and was not sufficient to address the research questions. Moreover, only a few slag sites have had basic documentation regarding site description and surface finds recorded (Chaiya 2007), while information for others has been limited to coordinates. Thus, all local slag deposits documented had to be reassessed in order to extract relevant data.

The 2012 fieldwork with an <u>unsystematic</u> surface survey strategy was conducted by the author assisted by two archaeologists: Yaowanit Charoenphuet and Thippawan Wongadsapaiboon. It should be noted that this fieldwork had no intention to resurvey Ban Kruat, but only visited each slag deposit previously recorded by the 2005-2007 surveys. Information recorded when visiting each deposit included the current condition and possible shape (e.g. mound or non-mound) and size of sites, how this evidence had changed from the 2005-2007 visit, any noteworthy features, archaeological and archaeometallurgical remains visible on the surface, and the concentration of these remains. The team would first try to locate each site recorded by previous surveys using a GPS device followed by fieldwalking around the potential area. When a site was found, the GPS device was used to record its coordinates. From previous archaeological work in Ban Kruat, it was learnt that metallurgical remains are not considered precious by landowners, and often removed, flattened, or destroyed to prepare land for agriculture or habitation. Probably owing to this, not all 67 slag deposits previously reported could be identified as they might have been destroyed or moved (Figure 5.2). Conversely, a few slag deposits that did not correspond to previously given coordinates were located. The slag deposits that have preserved their mound shape could be identified easily during the fieldwork, but the non-mound sites were problematic as metallurgical remains could be distributed in a wide area, possibly caused by bulldozing former slag mounds. Therefore, the author tried to identify this latter kind of site by their high concentration of slag and/or other metallurgical remains. Furthermore, interviewing landowners was very helpful for the identification of sites and gaining information about their original morphology and any changes occurring. Accessing each site, the surveying team tried to contact the landowner or head of community to explain the research in order to gain permission. Based on my previous experience in Ban Kruat, most of locations could be easily accessed, and landowners were amenable as long as they understood the reason of the visit.

5.1.2 Site selection and sampling strategy

According to the 2012 survey, slag was the most common cultural material encountered along with technical ceramics and ceramic sherds in lesser quantities. The surface assemblages are difficult to date as they generally lack type-finds (e.g. pottery); only two out of 67 sites have hitherto been radiometrically dated to the Iron Age (500BC-AD500) (see section 7.3.1). This means that there was at the time of writing no clear chronological sequence of slag sites in Ban Kruat, thus this research only pursued to investigate broad iron technologies practised in Ban Kruat instead of attempting to understand technological changes of iron production.

Different stages of investigation were designed in order to extract relevant data from archaeological and archaeometallurgical remains as much as possible under mentioned constraints. All slag deposits and archaeological and archaeometallurgical remains found associated were firstly preliminarily evaluated macroscopically, following the field assessment method by Bachmann (1982). The investigation of slag deposits considered their locations and types of sites (e.g. mound and non-mound), the distribution pattern of slag sites in each cluster, and archaeological and archaeometallurgical finds associated which would help to elucidate some issues, such as the activities involved (e.g. smelting, primary bloomsmithing, or manufacturing of objects), the relationship between slag sites and natural features (e.g. stream), the relationship between slag sites, and how workshops may have been spatially organised. Archaeometallurgical remains at each slag deposit were also examined visually to determine overall similarities and differences of metallurgical remains across different sites. However, as time and budget were insufficient, the examination of archaeometallurgical remains found at each site could not be done in great detail (e.g. no measurement was conducted at this stage). Therefore, least two iron production loci per site cluster were assessed in more detail and approximately 15-30 slag samples were collected per site depending on the availability of slag on the surface of each site. Other surface remains (e.g. technical and domestic ceramics) were collected if available (see Appendix C for summary and images of samples collected). Features, such as size, shape, weight, colour, porosity, magnetism, flow pattern, orientation that can be recorded with the naked eye and basic equipment (e.g. digital calliper, scale, and magnet) would be used for the classification of the materials into groups with similar characteristics, and facilitating initial interpretation of some technical questions; such as whether or not the slag was tapped. The measurement of the dimensions of slag, particularly smelting slag could be troublesome for their shape are all irregular (see examples in Chapter 7). Thus, the measurement of slag dimensions was done by consistently determining the maximum length, width, and thickness of each sample examined. These data were used to observe to what extent they could discern any group (see section 7.3.2). Density of some slag was calculated using this following formula: ρ (density) = m (mass)/v (volume). The mass was known by weighing samples on digital scale, while their volumes were known by submerging a small piece of each sample in measuring cylinder filled with water and measuring the differences of water displaced (i.e. initial volume without sample – volume with sample = volume of a sample).

Subsequently, some of these sites were selected for laboratory examination (mineralogical and chemical analysis) (see section 5.3 for analytical methods employed). Originally, metallurgical remains from at least two sites per cluster were hoped to be analysed in laboratory, but the preliminary visual comparison in conjunction with previous studies (Venunan 2011; Yoopom 2010) suggested a fair degree of similarity in slag and technical ceramics (see section 7.3.2). In light of this examination, and also bearing in mind logistical constraints, a single site of interest from each cluster was chosen for analysis (see section 7.2 for the justification for each site chosen). Seven slag samples from each site and some technical ceramics collected from different sites were analysed. Data generated would allow a discussion of technological practices. The cross-comparative study of different clusters would provide information regarding technological variation across the production landscape. Technological variation within a single site was assessed by examining samples from the excavated site of KDT2, with more intensive sampling of 23 excavated contexts.

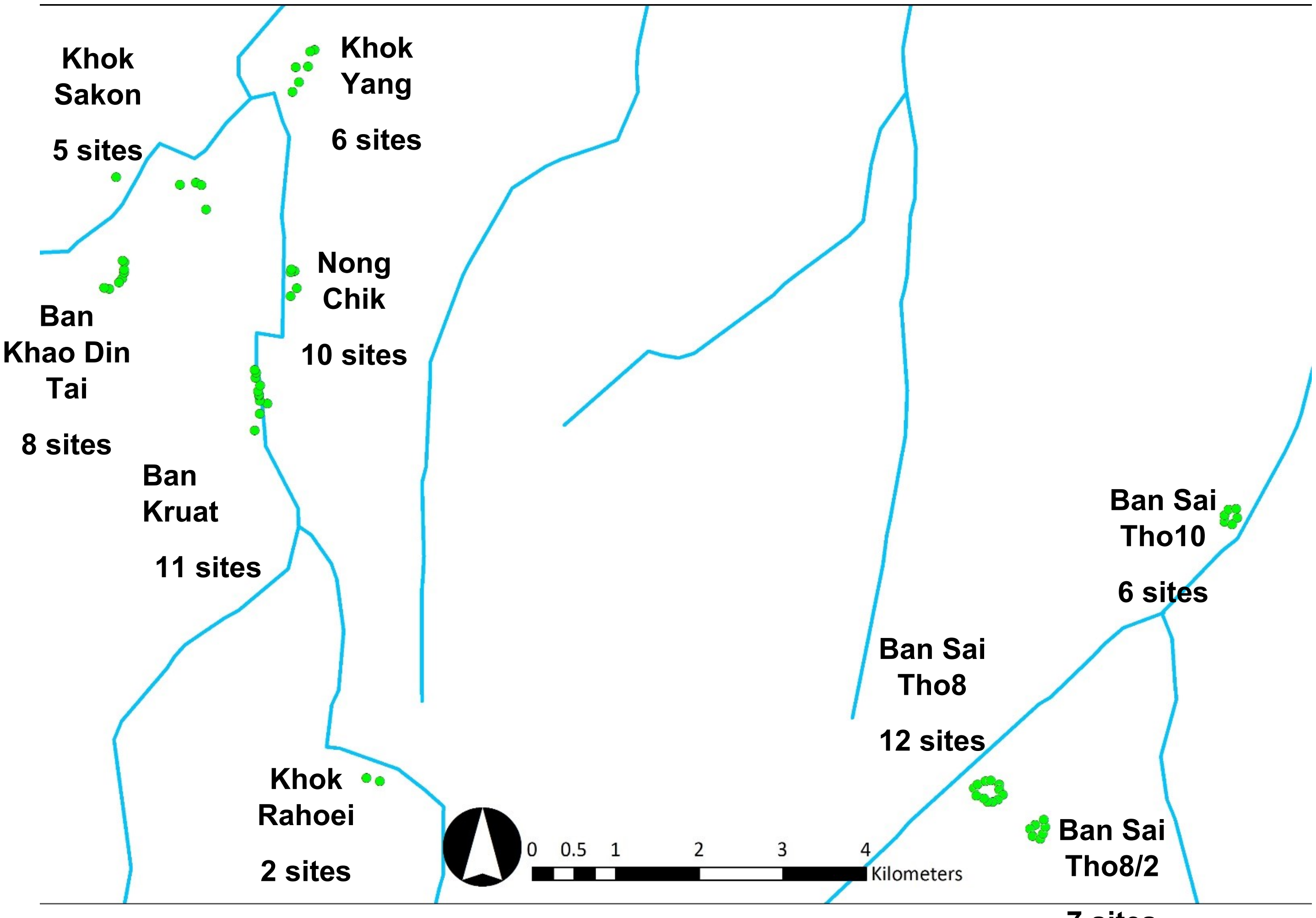


Figure 5.1 67 slag deposits documented by the 2005-2007 surveys.

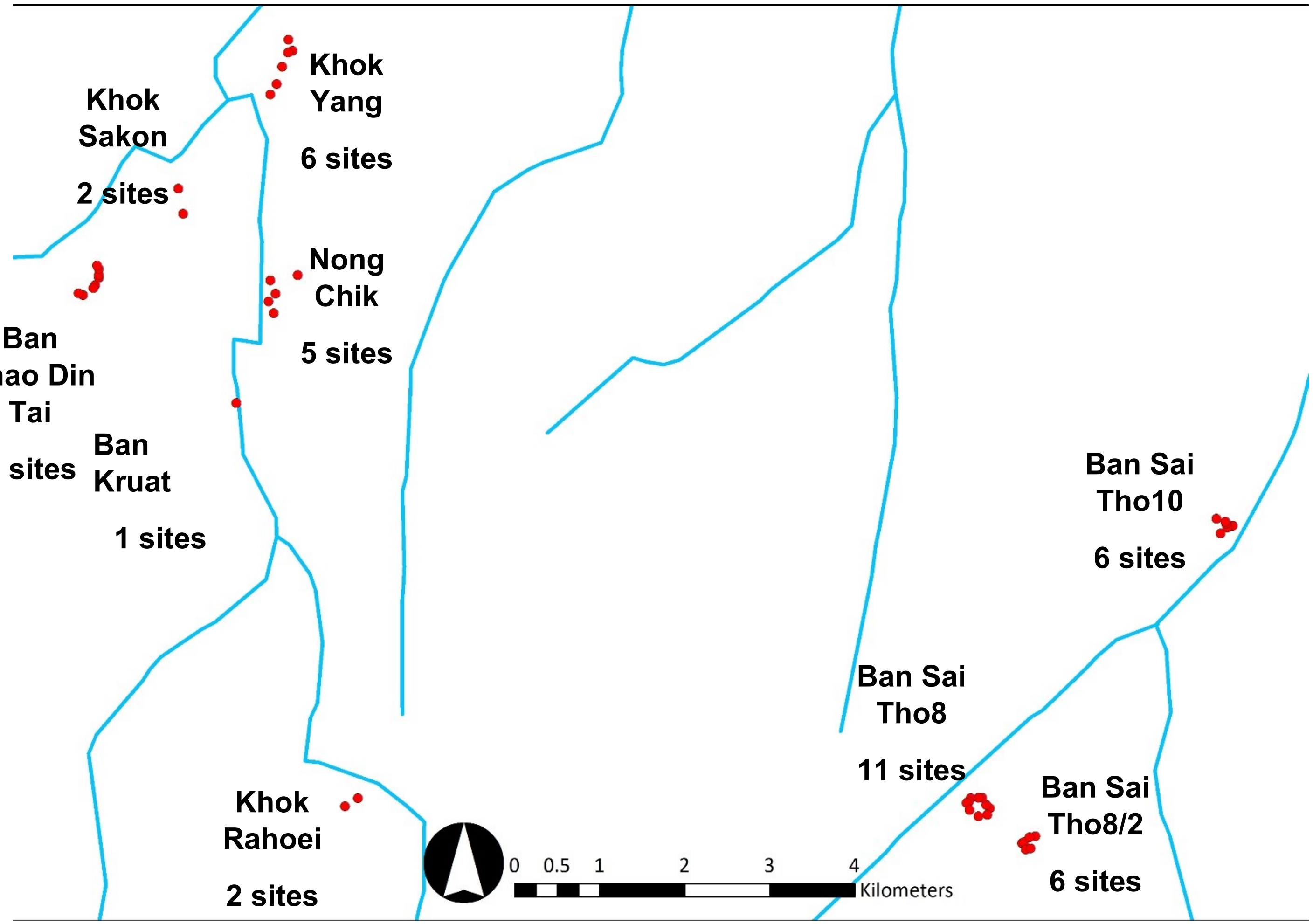


Figure 5.2 47 sites confirmed by the 2012 survey. The spatial distribution of some clusters (e.g. Khok Yang and Ban Sai Tho8/2 and 10) is found changed according to the 2012 revisit. For Ban Kruat cluster, the team could only visit one site; therefore, it is not clear how other 10 sites have been changed (see Chapter 7 for the result of the 2012 survey).

Considering the current chronological resolution for metallurgical sites in Ban Kruat, the reconstruction of local Iron Age iron technologies can be done with confidence by examining evidence from KDT2; however, better chronological contexts for other slag deposits, if obtained, will permit a better discussion of the development of these activities through time.

In total, 166 samples collected from 13 sites were selected for the laboratory analysis. Full documentation for the sites and samples selected for this research is provided in Appendices C and D respectively.

5.2 Laboratory-based analytical methods

Macroscopic examination was employed as the first step to provide preliminary technical information. However, the core of information that would help reveal the production sequence, identify technological traditions, choices, and constraints, and detect any technical variation within and between workshops, was obtained through mineralogical and chemical analysis using four analytical techniques, introduced below. All analyses discussed below were done at Wolfson Archaeological Science Laboratories, located at UCL Institute of Archaeology.

5.2.1 Optical microscopy (OM)

Visual examination of metallurgical assemblages indicated morphological similarity of the finds across different clusters. A cross-comparison of microscopic and chemical compositional characteristics of samples from different clusters was expected to test whether this observation remained true at different scales of analyses. OM was the first method to be employed to address this issue. OM is widely used in ferrous archaeometallurgy to characterise the crystal structure as a proxy to explain the formation and estimating the possible composition of examined samples (Bachmann 1982). Degrees of homogeneity or heterogeneity in microstructure can also be assessed. Since each phase tends to have its own optical properties (e.g. crystal or phase shape, colour, reflectivity) under cross-polarised light, a comparison with other studies as reference helps this study to identify any phase in the samples examined and preliminarily estimate chemical composition of samples (e.g. Bachmann 1982; Fell 1983; McDonnell 1986; Tholander 1987; Veldhuijzen 2005).

Three to four slag samples from each site along with other metallurgy-related samples (e.g. technical ceramics and laterite fragments and nodules) were subjected to this analysis. This allowed a large area of samples to be quickly examined to spot any interesting features for further investigations by SEM-EDS. In total, 42 slag samples, 11 ore samples, and seven technical ceramics were analysed with OM and SEM-EDS, providing a good overview of the remains.

5.2.1.1 Sample preparation and analysis

Each of selected samples was first cut with an abrasive tile cutter in order to observe the overall nature of the sample, and, then, the area containing typical (e.g. common phases presented) and interesting features (e.g. containing metallic or mineral inclusions) of approximately 1-1.5cm^3 were selected. Each sectioned sample was mounted in a block with epoxy resin with a ratio of resin to hardener of 1:4. The blocks were ground with abrasive paper from coarse (P120) to fine (P4000) and polished with diamond pastes of 3μm, 1μm, and 0.25μm grades to achieve a smooth surface. The polished blocks were then examined under a Leica DM4500 P LED polarisation microscope, equipped with a Leica DFC 290 HD camera. Micrographs of interesting areas were systematically (50X, 100X, and 200X magnification) obtained throughout the analysis.

5.2.2 Scanning electron microscopy with an energy dispersive spectrometry (SEM-EDS)

This instrument operates on the principle that an electron beam directed on the sample excites the surface of the sample and generates three types of signal relevant to these analyses, namely secondary electrons (SE), backscattered electrons (BSE), and X-ray photons. SE provides topographic information, whereas BSE reflects variation of chemical composition of the phases of the sample, with brightness being indicative of their relative density. The emitted X-ray radiation, measured by the EDS system, provides chemical compositional information of the area analysed (Pollard *et al.* 2007, 109-110).

This methodology allowed the results obtained from earlier OM phase analysis to be tested or re-evaluated. With SEM-EDS it was possible to pinpoint and analyse specific areas of interest within the samples, and the chemical composition of crystals and interstitial matrices could be measured. In addition, area analyses provided “bulk” chemical composition of chosen areas with or without residual inclusions. Moreover, features that could not easily be identified by OM could be characterised by this instrument.

Regarding the ceramic samples, the main purpose of their study was to provide supplementary information for the explanation of iron technologies, including their role and contribution to the smelting system and slag formation. However, a full investigation of technical ceramic production is beyond the aims of this thesis. Since conventional petrographic analysis was not employed to study of this material, OM and SEM-EDS was used as an alternative methodology to characterise their microstructures as well as any temper (e.g. quartz) added. Given their unconsolidated structures and abundance of quartz grains, it was decided that more reliable information on their bulk chemical composition would be obtained with WD-XRF (see section 5.3.3).

5.2.2.1 Sample preparation and analysis

The same samples prepared for OM were sputter coated with a layer of carbon approximately 15nm thick to increase the conductivity of the samples' surface and prevent an accumulation of charge. A JEOL 8600 Superprobe equipped with an Oxford Instruments INCA X-sight energy dispersive spectrometer system was used. All analyses were conducted at an acceleration voltage of 20kV, with a working distance of 11mm, an acquisition time of 50 seconds, and a beam current of 50nA. A cobalt standard was used to monitor any shifts in the beam current and peak identification. Analytical totals were checked routinely which showed that they varied between 98-102 wt% when analysing solid spots or areas. The totals could be as low as 85 wt% when porous areas (e.g. clay part) were analysed. The results were normalised to 100% to facilitate comparisons across the dataset and with previous studies, and to compensate for analytical losses caused by porosity and small fluctuations in beam intensity.

Phase analysis was based on 6-10 different spot analyses of the same phase, while "bulk" chemical composition was obtained by averaging at least three area analyses of the same sample at 500μm by 400μm. It is known that most samples concerning metallurgical waste (e.g. slag, ores, and ceramic) are generally dominated by oxide components (e.g. alumina (Al_2O_3), silica (SiO_2), manganese oxide (MnO)), but the SEM-EDS system cannot quantify oxygen accurately. Therefore, oxygen was added to each analysed elements according to their most stable valence by using stoichiometry. However, when analysing metal inclusions, the stoichiometry mode was not used. All SEM-EDS values are presented as percentages by weight (wt%).

Certified reference materials (CRMs) similar to materials studied in this thesis were used to monitor the accuracy and precision of the SEM-EDS system. Swedish Slag (Kresten and Hjärthener-Holdar 2001) was utilised for the evaluation of slag samples. BHVO-2 (USGS 1998b) and BCR-2 (USGS 1998a), both basalt, were also included as they to some extent chemically resembled laterite samples. In addition, the high alumina content in the basalt standards (13.69 and 13.74 wt%) could be used to evaluate this oxide in the archaeological slag and laterite samples. For comparison with the ceramic samples, NCS Clay DC60105 (China National Analysis Centre) and NIST76a burnt refractory (NIST 1992) were chosen. It should be noted that only basalt standards were prepared as solid blocks, whereas the other reference materials were analysed as powders pressed in aluminium cups, which were relatively more porous and resulting in lower original analytical totals (80-90 wt%). All certified values for the reference materials were converted into stoichiometric oxides for comparison with the data generated by this study (see full analytical results in Appendix A). The results showed that the instrument was precise, with coefficients of variation (CVs) generally below 10% suggesting a good level of replicability of the results. The accuracy of the instrument was very good when the concentration of elements was higher than 0.5 wt%, this is consistent with typical confidence limits for the instrument, empirically set around 0.5 wt%. Lower values are reported as indicative of presence or absence or as below detection limit (bdl). Peaks in the spectra were routinely checked to confirm the presence of some minor elements, which were commonly present in the samples of this research (e.g. Mg, P, V, and Cr), rather than relying only on the automatic peak identification software of the instrument.

5.2.3 Wavelength dispersive-X-ray fluorescence spectrometry (WD-XRF)

WD-XRF works on the principle that if the atoms in samples are excited by primary X-rays, as they de-excite they will produce secondary X-rays characteristic of the atom from which they came. Identifying the characteristic wavelength, individual elements can be identified, and their concentrations estimated based on the intensity of the emission. Unlike energy dispersive-X-ray fluorescence (ED-XRF) where energy detection and measurement are done simultaneously, in WD-XRF, different energies emitted are directed into a dispersion device and diffracted into different directions. A separate detecting system records the intensity of certain wavelengths. Compared to ED-XRF, WD-XRF is regarded to have better sensitivity and lower detection limits as the intensity of each characteristic wavelength is measured separately, but at the expense of longer analytical time (Pollard *et al*. 2007, 104-106; Pollard and Heron 2008, 42-43).

WD-XRF was used to provide quantitative bulk chemical information for all samples (i.e. slag, technical ceramic and domestic ceramics, clays, and ores). Unlike SEM-EDS, where specific areas are analysed, bulk chemical information obtained from this methodology represents the mean composition of the sample, assuming homogeneity. Thus, bulk chemical results should ideally be assessed together with a consideration of the samples' microstructure, as done here by OM and SEM-EDS.

5.2.3.1 Sample preparation

Samples for XRF analysis were prepared as pressed powder pellets. A minimum requirement of 4g of each sample was required to make a powder pellet. To minimise contamination from other material, the part of the samples that showed no visible signs of other material, vitrification, or corrosion was preferable. Only core parts of technical ceramics were selected to avoid any attached slag or vitrification, and equally slag corrosion products and large inclusions were removed as much as possible.

The specimens were crushed using a steel mortar and pestle and then milled in a planetary ball mill to achieve a powder with a grain size of less than 50µm to minimise XRF diffraction and refraction by crystalline structure of the material analysed. Tungsten carbide balls and steel pots were used to mill slag samples, while technical ceramic, domestic ceramic, clay, and laterite samples were milled in agate pots and balls. The powders were dried at 105°C for at least 24hrs to get rid of moisture. Each sample powder was mixed with a wax binding agent at a ratio of 4g of sample to 0.9g of wax and compressed into a pellet using a hydraulic press at 15 tonnes for 2.5 minutes. Although the procedure was set to minimise contamination, the use of a steel pot for slag has evidently been shown to introduce high amounts of cobalt oxide (Co_3O_4) and tungsten oxide (WO_3) to the analysis (Iles 2011, 128). These elements were therefore not used for interpretation.

5.2.3.2 Analysis and oxides chosen for interpretation

All samples were analysed by a WD-XRF Spectrometer Philips PW2400 at the Department of Geosciences, University of Fribourg, Switzerland, using the UNIQUANT 5 analytical programme. The results were reported as wt% and normalised to 100% in order to facilitate comparisons between samples as the original analytical totals varied caused by matrix effects of each material. Unnormalised data were not given to the author. These analytical totals fluctuated depending on the materials between 90-99 wt% for slag samples, while the totals of clay-rich samples (technical ceramics, domestic ceramics, clay, and laterite) varied between 77 wt% and 90 wt%. This fluctuation is perhaps due to matrix effects (interferences between the components of multicomponent mixtures (Pollard *et al*. 207, 307)), presence of carbonates (no LOI was calculated), and remaining porosity in spite of grinding and pressing. Like the SEM-EDS system, oxygen cannot be measured by the WD-XRF, so all elements were converted to oxides by stoichiometry. All iron was converted to FeO by stoichiometry. This valence of iron was the most commonly occurring valence of iron in slag samples suggested by OM and SEM-EDS (e.g. fayalite (Fe_2SiO_4), hercynite ($FeAl_2O_4$), and wüstite (FeO)). By default, FeO is reported for all iron oxides for simplicity and to facilitate comparisons between the materials and mass balance calculations, but the author was aware that multiple oxidation states could occur. For example, iron in laterite which was likely to be iron hydroxides ($Fe(OH)_2$ or FeO(OH)) rather than the simpler iron oxide (FeO).

The full analytical results from WD-XRF provided the reading of 52 oxides and elements (see Appendix H). Of these, certain oxides and elements (e.g. MgO to FeO, strontium oxide (SrO), barium oxide (BaO), and rare earth elements (REEs) (e.g. lanthanum (La), cerium (Ce)) are arguably meaningful in the analysis of smelting materials and reconstruction of smelting technology as they show the correlation between slag and parent materials (ore and technical ceramics) (e.g. Bachmann 1982; Charlton *et al*. 2010; Crew 2000; Desaulty *et al.* 2007; Navasaitis *et al.* 2010; Thomas and Young 1999). In this research, 19 oxides were considered, and their relationship between these oxides and the parent materials is explained in Table 5.1. These oxides allowed the author to explore some issues concerning smelting technology and technical variability in Ban Kruat iron production (see sections 8.4.1 and 8.4.2). Nonetheless, due to the analytical performance of the instrument, the reliability of these chosen oxides needed to be assessed first.

	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3
Ore	■	■	■		■	■	■	■	■	■	■	■		■		■	■	■	■
Clay	■	■		■		■									■				
Fuel Ash			■	■	■								■	■		■			

Table 5.1 Some oxides considered for the technical interpretations

An assessment of the accuracy and precision of the instrument was done in a similar manner as for SEM-EDS. For comparison with the slag samples, Swedish Slag and SL-1 Blast Furnace Slag (NRCAN 2013) were included. BHVO-2 Basalt (USGS 1998b) and BCS-301/1 Lincolnshire Ore (BAS 2011) were utilised for comparing with the ore samples. In addition, the blast furnace slag and basalt standards were chosen for their comparably high alumina levels with the slag and ore samples. For comparison with the ceramic samples, the following two reference standards were utilised: NIST76a Burnt Refractory and BCS776-1 Firebrick (BAS 1983). These standards were included in the instrument whenever the samples were being analysed. Detailed analytical results of the CRMs are included in Appendix B, and a brief summary is presented here.

In terms of precision, the CVs of most compounds calculated are below 6% indicating that the results were very precise and replicable compared with the same CRMs analysed on 10th April and 18th November 2014. Exceptions could be seen in the oxides with low concentrations (vanadium oxide (V_2O_5), chromium oxide (Cr_2O_3), lanthanum oxide (La_2O_3), and cerium oxide (CeO_2) where the CVs were above 15%.

The accuracy appeared to be varied from standard to standard which was likely due to matrix effects. For slag reference standards, relative errors of Al_2O_3, SiO_2, phosphorus pentoxide (P_2O_5), potassium oxide (K_2O), calcium oxide (CaO), V_2O_5, manganese oxide (MnO), and iron oxide (FeO) were below 15%. The accuracy decreased significantly when dealing with light oxides (i.e. sodium oxide (Na_2O) and magnesium oxide (MgO) or oxides with low concentrations, including titanium oxide (TiO_2), V_2O_5, Cr_2O_3, SrO, zirconia (ZrO_2), BaO, La_2O_3, and CeO_2. For ore reference standards, while SiO_2, P_2O_5, K_2O, MnO, and Fe_2O_3 had relative errors below 10%, the errors of oxides such as Al_2O_3, CaO, and TiO_2 were varied between two standards (below 20%). The accuracy of ceramic reference standards were below 15% for most oxides (i.e. Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2, and MnO). Fe_2O_3, Cr_2O_3, BaO, and SrO had higher errors, probably due to their lower concentrations.

Overall, the assessment indicated that the precision of the instrument was good meaning that the instrument had been stable throughout the course of this analysis, and the results were not significantly different between two analyses. In terms of accuracy, affected by matrix effects, the relative errors of most oxides shown in Table 5.1 (i.e. Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2, MnO, and FeO) were generally below 15%. In contrast, V_2O_5, and Cr_2O_3 were less reliable. Unfortunately, accuracy for remaining oxides (CuO to Nd_2O_3) could not be assessed for no suitable standards were available during the analysis. Arguably, although the determination of some selected oxides was not good, their values still have indicative meaning (i.e. presence or absence). The results generated are considered meaningful for internal comparisons and discussion, allowing technological discussion and the identification of general compositional trends across sample groups, but it is acknowledged that accuracy may not be sufficient for provenance studies based on slag inclusion analysis.

5.2.3.3 Note on the calculations of SD and CVs from the chemical compositional data obtained

SD and CV values were calculated and presented throughout the results chapter for several variables (Chapter 8) in order to explore the degrees of the variations of the values in each group examined. When encountering lost values (reported as bdl), they were replaced by the lowest values reported in the same series assuming the lost values were closer to the detection limit than zero. It was decided that replacing the values with zero or leaving them as blank could distort the calculated SD and CV more than the replacement with the lowest values. It should also be noted that if for a particular series more than half of the whole set were below detection, then, average, SD and, CV were not calculated.

This practice was also implemented for the preparation of the compositional data for PCA (principal component analysis). If the variables (oxides) were found to have too many too many lost values, they were excluded for that particular calculation. For the variables with some lost values variables, those missing values were replaced with the lowest values in the same series.

5.2.4 X-Ray diffraction (XRD)

XRD is a qualitative method, employed to determine the lattice spacing in crystalline structure which allows the identification of chemical compounds of sample in question. It is widely used for identifying mineralogical structures of inorganic materials (e.g. clays and ores). The most common form of sample used is in a fine powder state that randomises the minerals in the sample. A powdered sample is placed on a thin glass slide and inserted in the diffractometer, which is consisted of three components: X-ray tube, sample holder, and X-ray detector. The sample is irradiated by a collimated beam of monochromatic X-rays. The detector rotates around the sample and records an interaction of the beam and the sample (diffraction of the X-rays from the successive atomic layers in the subsurface crystal lattice of the sample). This interaction creates secondary diffracted beam of X-rays related to spacings in the sample crystalline structure, and, according to Bragg's Law ($n\lambda=2d\sin\Theta$), the diffraction pattern created is characteristic to certain mineral. Therefore, each mineral phase present can be identified by its pattern (Malainey 2011, 479-480; Pollard *et al*. 2007, 114-116).

5.2.4.1 Sample preparation and analysis

The spare milled samples prepared for WD-XRF were used for this analysis. The powder of each chosen sample was dried overnight again to ensure that it was dry. The instrument used was Benchtop XRD Rigaku MiniFlex 600. A small quantity of milled sample was placed on a small glass plate and installed into a clamp. The analysis and interpretation of spectra were done by the Rigaku PDXL application. The installed library was quite limited but able to suggest the minerals presented in the sample. The results were compared to related studies on laterite to determine their reliability.

5.2.5 Laboratory firing experiments

Some technical ceramic samples from KDT2 were refired to gain more information regarding their refractoriness and behaviours in high-temperature condition. The information would benefit an evaluation of the chemical contribution of technical ceramics to slag formation. An experiment was set to 1,300°C; this was done in an electronic furnace. This setting to this temperature was suggested by the estimation of the melting (liquidus) temperature of slag samples accordingly to the FeO-SiO_2-Al_2O_3 ternary diagram (Figure 8.65). According to the diagram, the highest melting point of some slag samples were around 1,300°C; therefore, this setting was to assess to the quality of technical ceramics under this said temperature.

The samples were left inside the furnace at the room temperature (approximately 15-20°C) and, then, raised to 1,300°C. To reach this set temperature, the furnace took around 1hr 30mins. The samples were in this temperature for around 2hrs and left until the furnace was cool enough to take the samples out for inspection. The result of this refiring and related comments are discussed in Chapter 8.

5.2.6 Etching metallic iron

Etching a polished metal surface intended to reveal differences in grain orientation and microstructure by intentionally corroding the metal using the appropriate etching solution. In this research, 2% natal solution (100ml ethanol and 2ml nitric acid) was used (Blakelock 2012; Scott 1991, 69). An iron fragment of interest was prepared using the same procedure for the blocks for OM and SEM-EDS. A polished sample was then left in the solution for 1-5 seconds and washed with tap water to stop the reaction. Each etched sample would subsequently be examined under OM to identify the type of iron.

Chapter 6 Archaeology of Ban Kruat

6.1 Introduction

The review presented in Chapter 3 and 4 already highlighted the limitations of local archaeological information, and the need to explore the larger picture in order to propose of a possible model for iron technology, production, and its social organisation. While remaining conscious of those challenges, this chapter presents a summary of what is currently known of environmental and socio-cultural settings, and their evolution over time. By integrating this currently known information of Ban Kruat with what was discussed in Chapters 3 and 4, this review will illustrate the potential of the use of the archaeology of lower Northeast Thailand to help improve the fragmentary picture of Ban Kruat archaeology. Moreover, this information will provide a necessary framework for the interpretations offered in later chapters.

6.2 Environmental settings

Ban Kruat is located in Buriram province, lower Northeast Thailand, close to the Cambodian border (Oddar Meanchey province), approximately 290 km east of Bangkok and 140 km northwest of Siem Reap (Angkor). The site is situated between the Upper and Middle Mun River Valleys and on the corridor between two important natural features: on the southern edge of Thai Khorat Plateau and the Cambodian Tonle Sap basin, separated by the *Dângrêk* Range, a natural political border of Thailand and Cambodia (Figure 6.1).

Ban Kruat consists mainly of the terrace (160-190m) and upland zones (190-500m) which are part of the *Dângrêk* Mountains. As the range stands to the south of Ban Kruat, its terraces are north-facing. Their current use is for rain-fed and irrigated agriculture, whereas the upland is used for growing rubber trees and cassava. The choices of upland agriculture are to some extent dictated by the soil groups that are predominantly unsuitable for rice agriculture, but appropriate for dry crops (Land Development Department n.d.) (Figure 6.2).

The area is supplied with water fed through various local small streams (i.e. Huai Sai Taku, Huai Seo, Huai Ta-baek, and Huai Thamnop) that originate in the *Dângrêk* Range. They flow northward through Ban Kruat to join the Mun River (Burirum Irrigation Project 2004) (Figure 6.3). The local ancient communities are likely to have benefitted from these water sources for daily life, local agricultural, and craft productions, source of clay for the ceramic production, and as inland waterway for transportation. The reliance on these small streams is likely supported by the spatial distribution of the ancient ceramic and iron production workshops close to these streams (Lertlum et al. 2008, 51-57) (Figure 6.4).

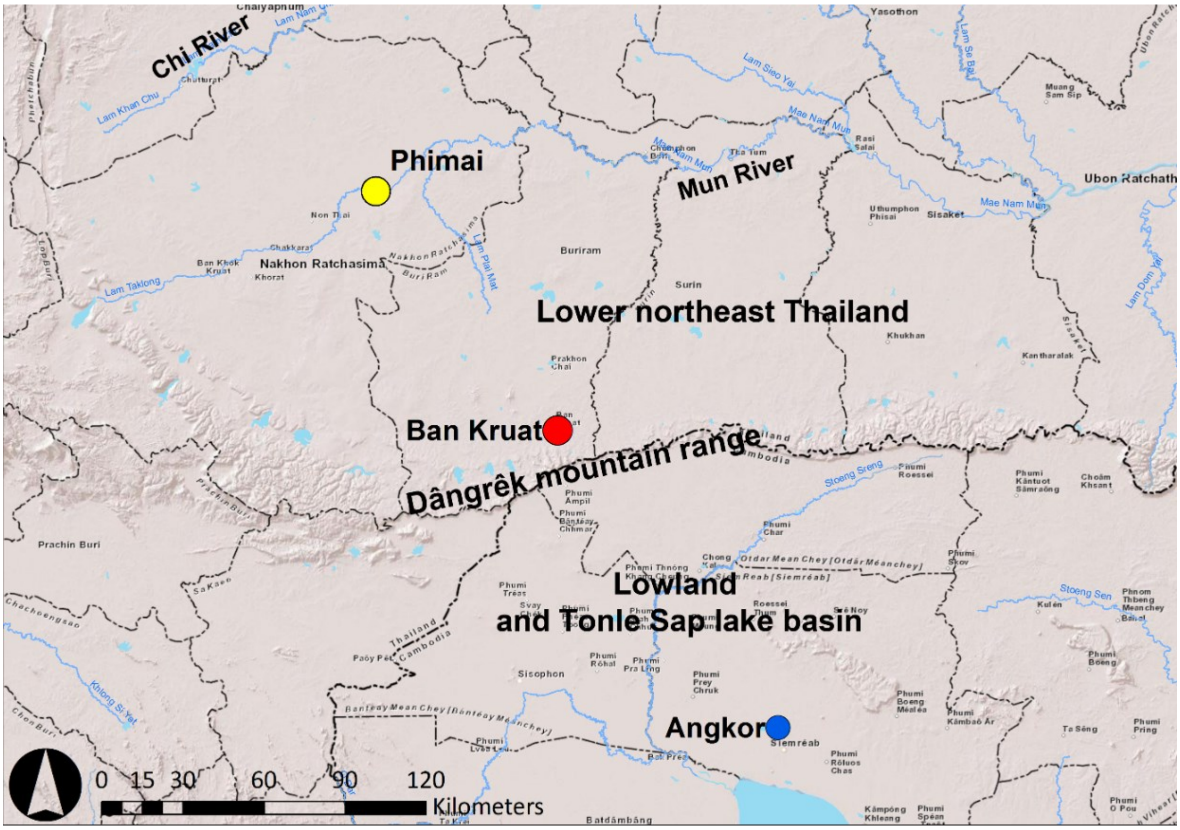


Figure 6.1 Map shows a geographical difference between Khorat Plateau in Thailand and lowland in Cambodia which are bordered by the Dângrêk Mountain Range

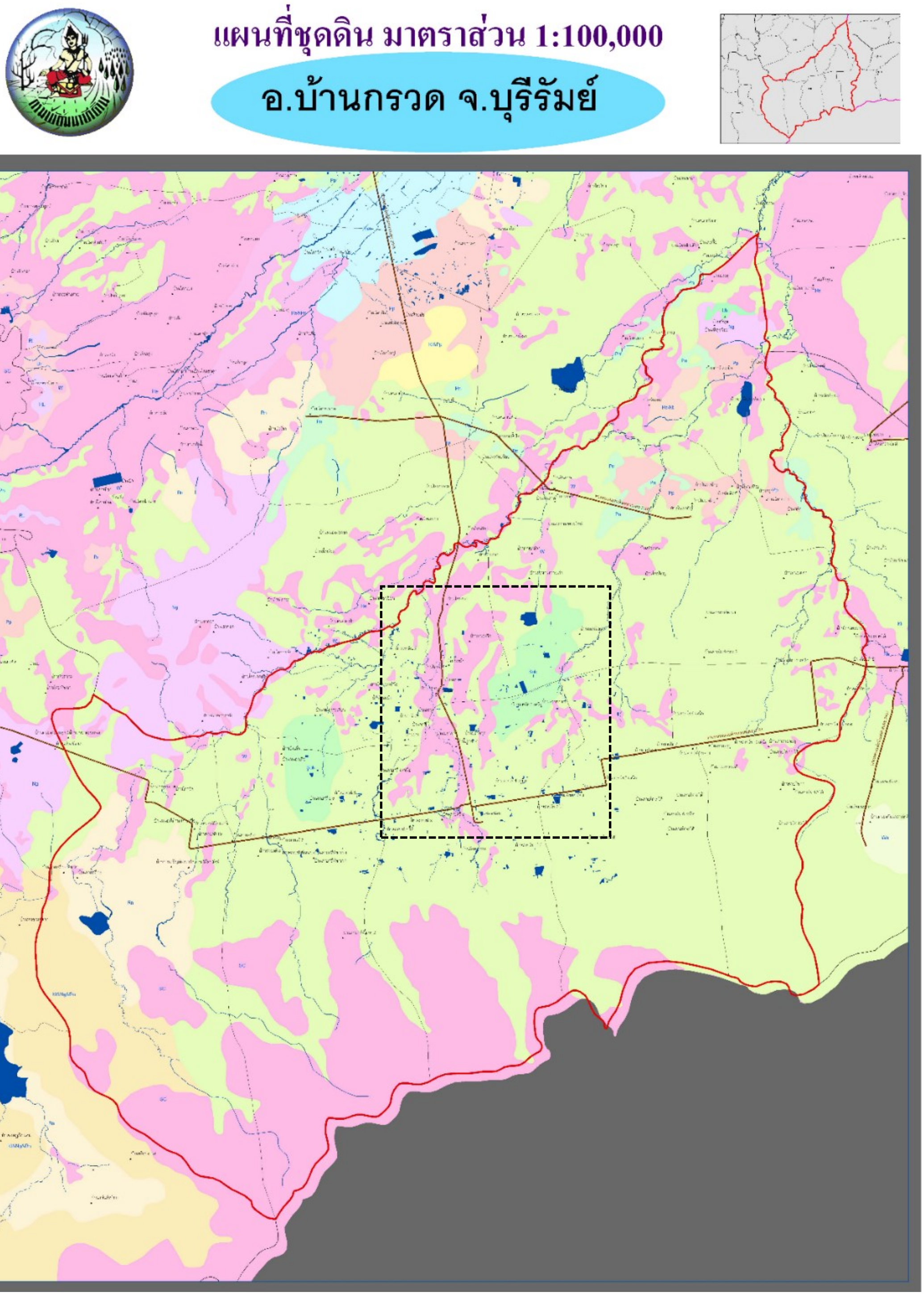


Figure 6.2 Map shows soil groups in Amphoe Ban Kruat. The soil that is suitable for rice agriculture is coded by dark pink (Re group). The area in the dash-line box is where the ancient industrial remains and Khmer temples are located.

(Adapted from Land Development Department n.d.)

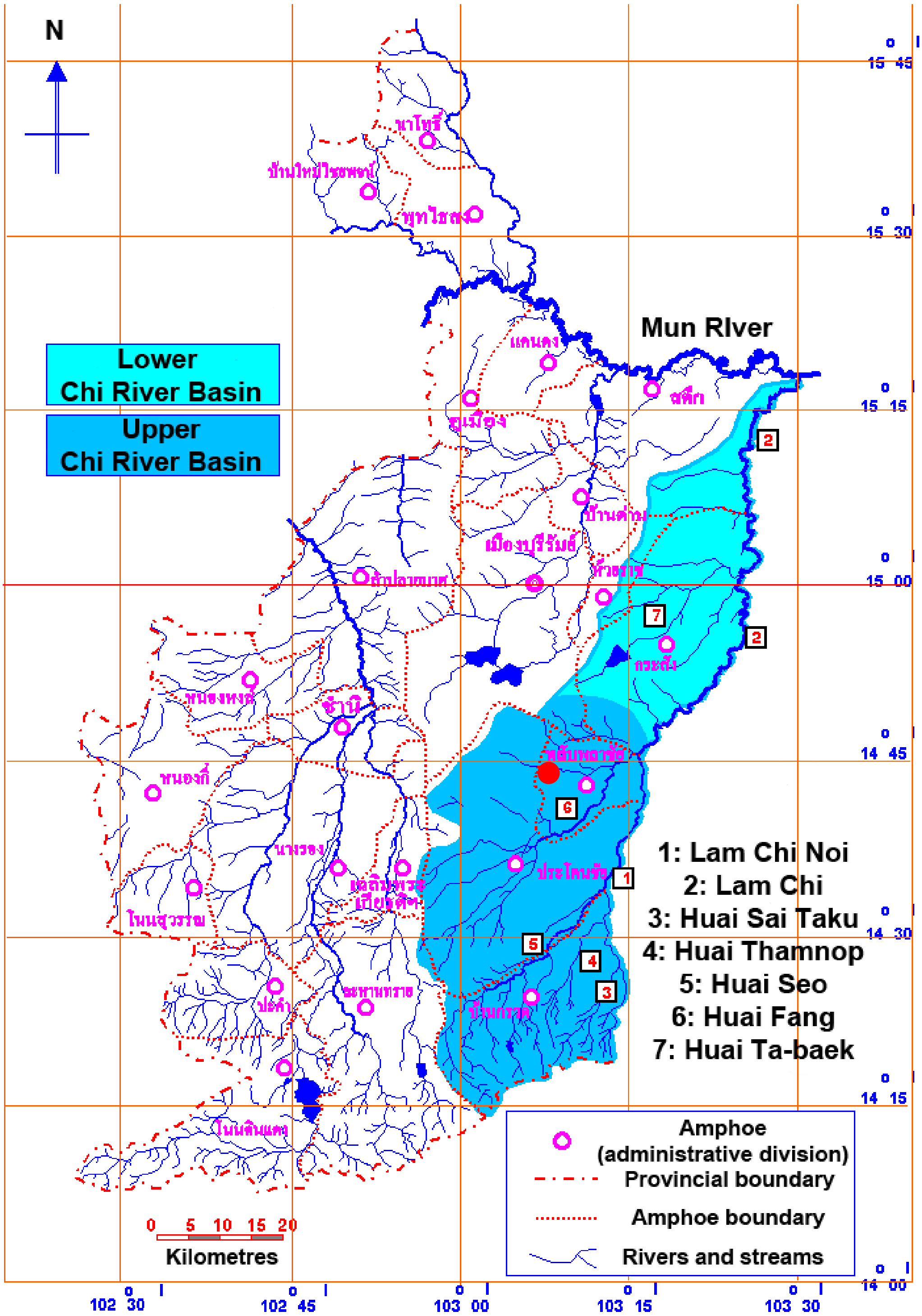


Figure 6.3 Map shows the location of Ban Kruat (red dot) in association with local streams and the Mun River

(Adapted from Buriram Irrigation Project 2002)

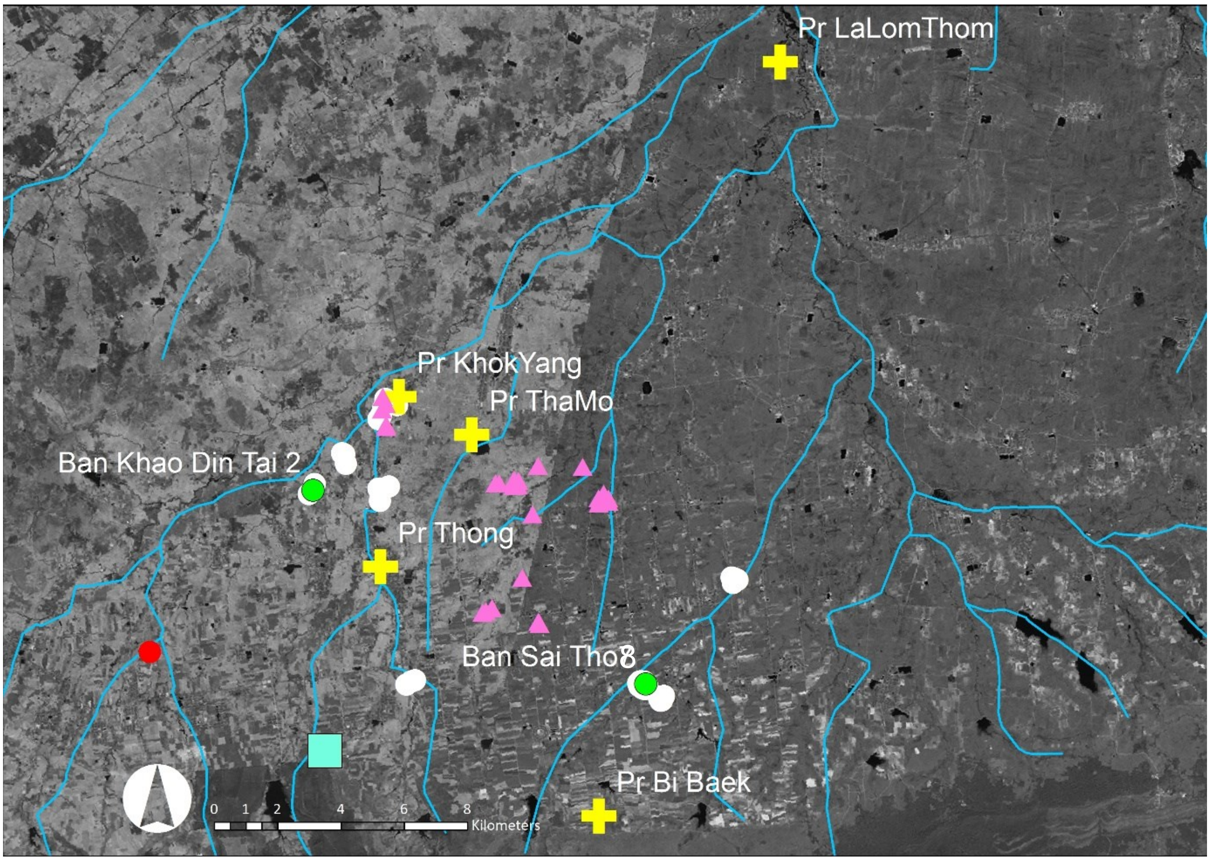


Figure 6.4 Map shows archaeological sites known in Ban Kruat. Iron Age: Ban Bueng Noi (red dot), Ban Khao Din Tai2 and Ban Sai Tho8 (green dots). Angkorian period: quarry (light blue squares), ceramic kilns/deposits (pink triangles), Khmer temples (yellow crosses), and Iron slag deposits (white dots)

The *Dângrêk* Mountain Range has sustained inhabitants in many ways. In addition to being a source of water, passes situated along the mountains have allowed the movement of people who have lived on both sides of the range (Figure 6.5). The great benefit of these passes became evident in the 13th century AD. Probably based on previous knowledge of communication routes, Angkorian Khmers paved a northwest route through the pass where Prasat Ta Muen was erected as a resthouse (*Dhammasala*) to support travellers (Hendrickson 2009, 2010, 2011). Remote sensing suggested that the selection of this pass for the route might be due to the ease of accessibility as it had the least slope compared to other passes (Tanlasanawong *et* al. 2007, 23-24). Nonetheless, in Ban Kruat, no resthouse has been reported, but one may contemplate that the-11th-century-AD Prasat Bai Baek, located on the spot just passing the corridor, might have played a comparable role.

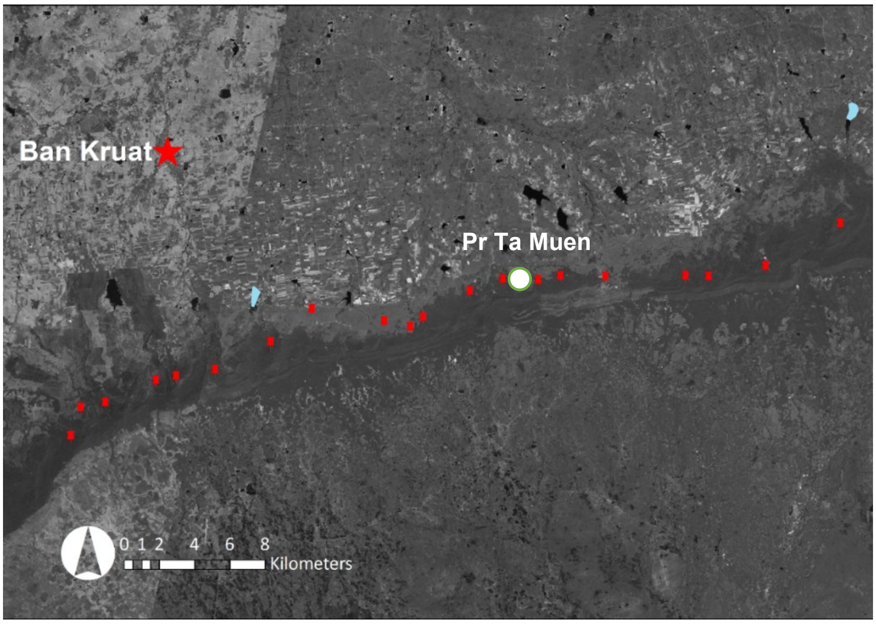


Figure 6.5 Some mountain passes near Ban Kruat (red icons)

Forest products, especially timber, thus, charcoal might have been another contribution from the range which was necessary for ancient production activities. Although, there has been no palaeoenvironmental assessment in this area, the existence of local ceramic and iron production suggests that the artisans might not have had a problem finding a sustainable charcoal supply. The range also offers sources of sandstone, one of which is located in Ban Kruat and quarried for the constructions of nearby Khmer temples, including the Ta Muen group, Phnom Rung, and Bai Baek (Uchida *et al*. 2010, 552-554) and manufacturing of Khmer stone markers. This stone quarrying is further supported by quarrying marks left on a sandstone outcrop in Ban Kruat (Figure 6.7) and the Angkorian inscription at this site (Karunchit 1992, 172). The exploitation of mountain clays is suggested by petrographic analysis of pottery fragments from the Iron Age Ban Bueng Noi (Archaeology section 2004, 85).

Figure 6.6 Angkorian decorative architectural component (left) and stone marker (right)

Figure 6.7 Quarrying marks on sandstone in Ban Kruat

On the basis of the data presented, the environmental setting of Ban Kruat appears to have supported habitation and promoted industrial activities as well as the movement and communication of populations and items. Although rice agriculture was viable, its productivity and yield are uncertain. Broadly speaking, the geography, geology, and environment observed in Ban Kruat are similar to other areas situated along the northern side of the *Dângrêk* Mountain Range (see section 3.2).

As for metal resources, based on the geological map (Figure 3.5, 3.6, 6.8, and 6.9), no typical metal ores are identified locally, as is the case in most parts of Northeast Thailand (see section 3.2). Concerning the source of iron necessary for iron production, potential sources may be found in the western edge of Northeast Thailand, Central Thailand, and Cambodia. With support from existing exchange networks belong to each period, the production in Ban Kruat might have been supplied by the ores from these locations, but there is no evidence supporting this speculation. In contrast, more widely available resources locally are the extensive deposits of laterite – but their possible use as an ore for ancient iron smelting remains debated (see sections 3.2 and 4.3.3.3). Remote sensing survey in Ban Kruat revealed a high concentration of this material favouring the hypothesis made by LARP (Lertlum *et al.* 2008, 23, Figure 2-7, 201-202) (Figure 6.10). Archaeologically, this material was extensively procured, likely from local sources, for the construction of local temples during the Angkorian period. Nonetheless, before the present study, direct evidence was scarce to address the issue concerning the use of this material in the local iron smelting industry.

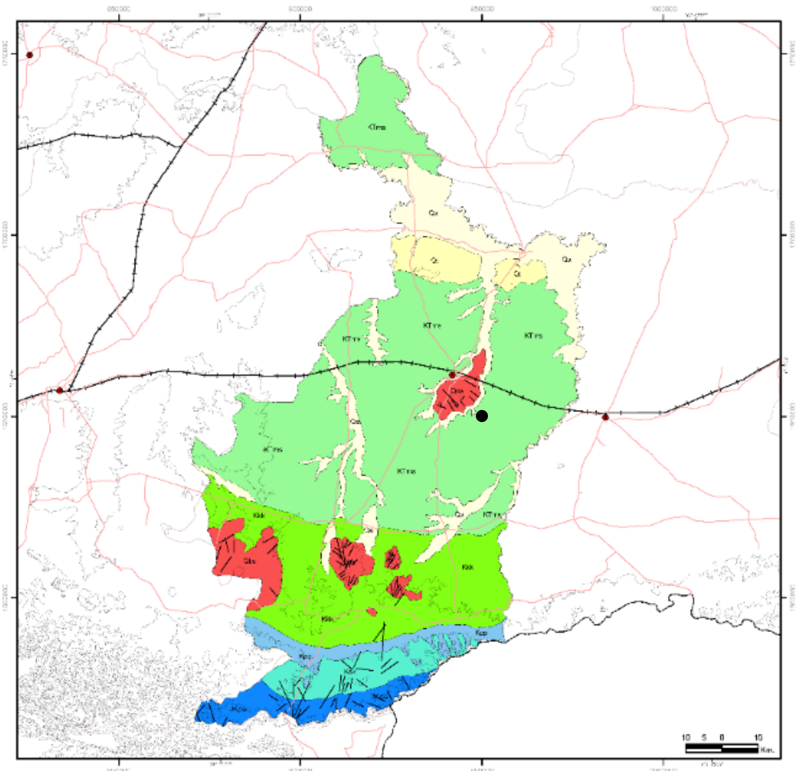


Figure 6.8 The geology of Buriram province. Igneous rocks (red) only appear in some areas in contrast to sedimentary and metamorphic rocks (other colours) that cover the province extensively. Ban Kruat (black dot) is situated on top of the large sandstone outcrops (light green, light blue, and mid blue).

(Adapted from Department of Mineral Resources, 2007)

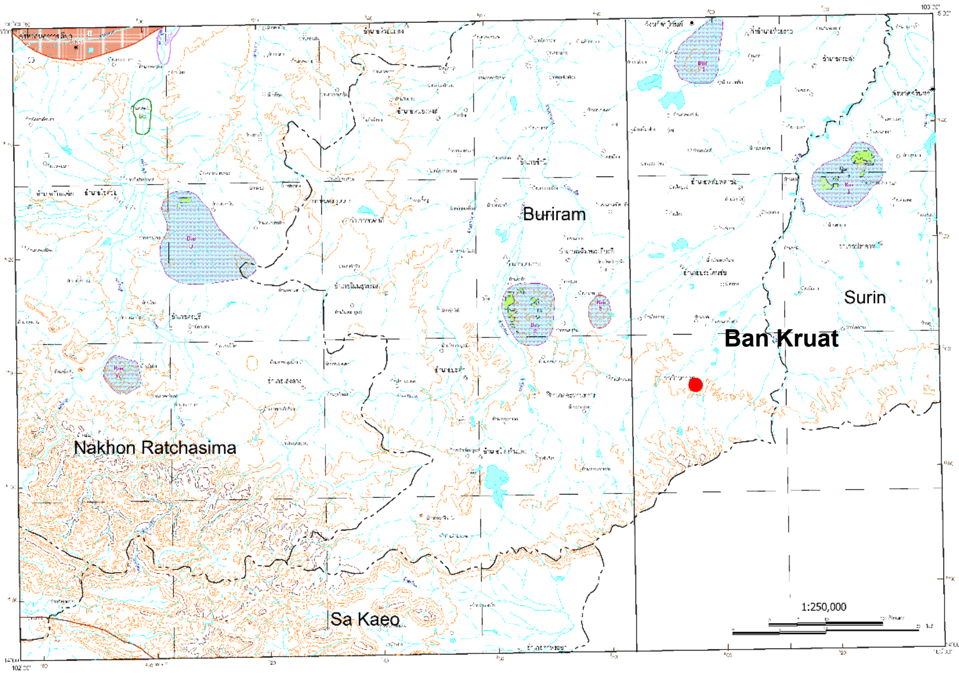


Figure 6.9 Mineral availability with modern economic potential in Buriram. Noticeably, the locally available geological materials include basalt, ball clay, gravel, and sand, but no metal ore resources have been recorded.

(Adapted from Department of Mineral Resources, 2001)

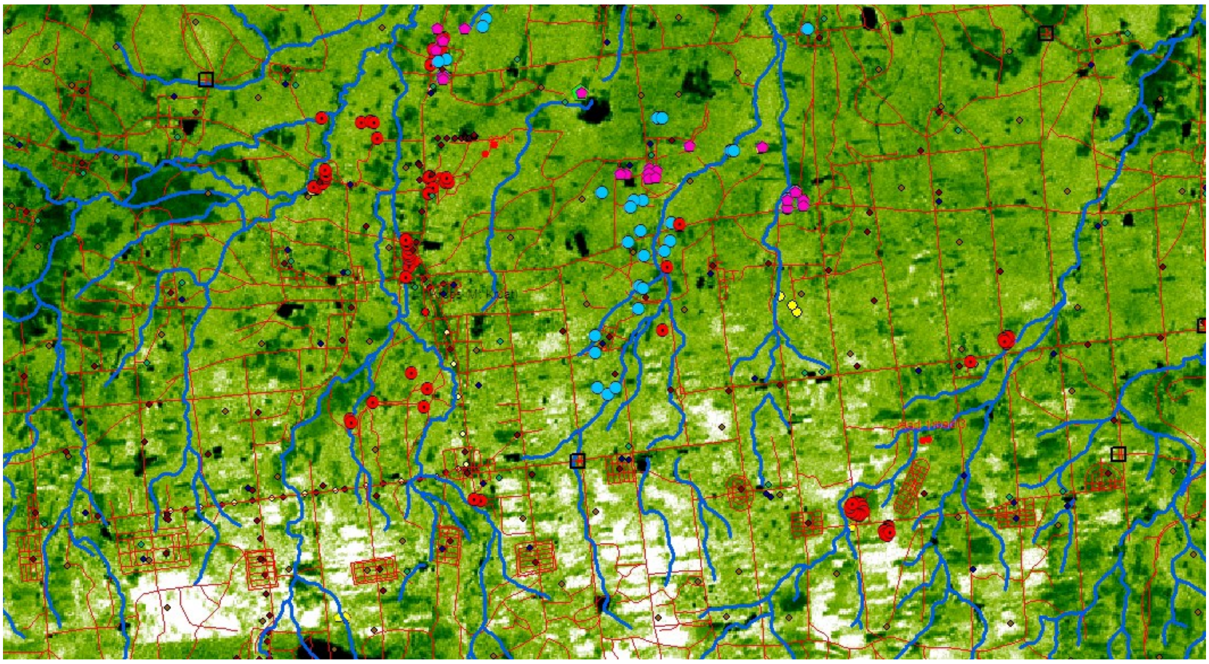


Figure 6.10 Remote sensing survey of Ban Kruat area showing the concentration of laterite (green colour) within the area (Channel 4/5 Index – lower (light) to high (dark) concentration). The symbols represent slag concentrations (red dots) and ceramic mounds (blue and pink dots). The iron slag deposits presented are according to LARP's survey in 2008. The quality of laterite has not been fully investigated.

(Image: Lertlum *et al.* 2008, 23)

6.3 Archaeological sequence of Ban Kruat: a current understanding

Ban Kruat came to the awareness of scholars in the early 20th century in response to the emerging attention paid to Angkorian Khmer ceramics found in this area (Brown 1988, 44; Prommanoj 1989). Since then, the research trend has been largely fixed on this subject (e.g. Brown 1981, 1988; Chandavij and Chandavij 1989; Ea 2008, 2010; Prommanoj 1989; Thammapreechakorn 2009; Wong 2010). Essential information on the archaeology of Ban Kruat was mainly generated by the archaeological works during 1980s which documented the ritual (i.e. temples) and industrial remains (i.e. ceramic production) belonging to the Angkorian period (Chandavij and Chandavij 1989; Prommanoj 1989; Srisuchat 1989). In addition, the iron slag mounds of Ban Sai Tho8 south (STH8) (corresponding with Ban Sai Tho7 in the excavation report (Lertlum *et al.* 2010) were recorded and thought to be of the Angkorian Khmer origin (Chaikulchit 1997; Srisuchat 1989, 118). No known Khmer settlements or early occupation were mentioned in the report (Srisuchat 1989).

Subsequently, in 2000, an excavation was commenced at the Iron Age site of Ban Bueng Noi, largely dated by the presence of Phimai black pottery (Archaeology Section 2004). This cemetery illuminates an early occupation in Ban Kruat, which fits broadly with lower Northeast Thai and Northwest Cambodian Iron Age communities (Archaeology Section 2004). This programme was followed by the Thai-Cambodian Living Angkor Road project (Lertlum *et al.* 2008; Lertlum *et al.* 2010; Tanlasanawong *et al*. 2007). The archaeological programme ran between 2005 and 2010 and posited the significance of the area being an Angkorian industrial locale for various products, certainly Khmer ceramics, sandstone, and iron (Lertlum *et al*. 2008, 39, 56-58). On this basis, the project went on to focus on metal production by documenting 67 slag mounds and excavating two chosen slag mounds: Ban Khao Din Tai (KDT2) and STH8. The author of this thesis participated in both excavations (Lertlum *et al.* 2008; Lertlum *et al.* 2010). The early scientific dating programmes pointed the activities at these two sites to the Angkorian Khmer period (Lertlum *et al*. 2008, 182; Won-in 2011; Yoopom 2010); although, there has been a possibility that STH8 may belong to the Iron Age (Lertlum *et al*. 2010, จ). The excavations generated valuable metallurgical data providing a great insight into Angkorian iron production (Lertlum *et al*. 2010; Yoopom 2010).

To date, the cultural sequence of Ban Kruat has been built upon sporadic archaeological works being done in the area, in contrast with the Upper Mun River Valley where archaeological evidence for each consecutive period is better recorded (see Chapter 3).

The evidence from Ban Kruat illustrates the sequence from the Iron Age to the Angkorian period that is consistent with broader knowledge about lower Northeast Thailand giving already a good picture of its social development and the local activities. Nonetheless, with a recent dating programme done for this thesis, concentrating on excavated features related to iron production (see section 7.3.1 for detailed discussion on the dating programmes), it is possible to further refine the chronology and an understanding of how Ban Kruat progressed through time.

The narration in this section will thus follow this chronological sequence, which has been revised by the recently obtained dates, to outline its socio-cultural setting. References to the broader region, discussed in Chapter 3, are cited as appropriate, hoping to link Ban Kruat to neighbouring areas. The metallurgical remains will only be briefly discussed here before being explored extensively in the next chapter.

6.3.1 The late Iron Age of Ban Kruat (ca 200BC – AD550)

An early occupation before the appearance of the Khmers has been characterised by three archaeological sites, i.e. Ban Bueng Noi (Archaeology section 2004), KDT2 (Lertlum *et al*. 2008), and STH8 (Lertlum *et al*. 2010). All of them are non-moated and likely to have sat on natural high ground close to small streams, at least for STH8. No landscape manipulation has clearly been seen archaeologically. As such, it is possible that the water supply and flooding might have not been significant issues for Ban Kruat. Available evidence indicates the presence of three different activities: burial ritual, domestic occupation, and iron production.

First, burial contexts were identified at the sites of Ban Bueng Noi and STH8. Ban Bueng Noi, likely to have been occupied only in the Iron Age, provided the best picture for that period. Secondary burial was a dominant ritual feature practised with exceptions of two flexed burials; each individual to some extent was endowed with typical Iron Age offerings, including Phimai black pottery, glass beads, burnt rice grains, and iron and bronze artefacts (Archaeology section 2004, 85-89) (Figure 6.11-6.13). In addition, the custom of the endowment of rice in the grave was common among the sites in the Upper Mun River Valley (IA II-IV) (see section 3.3.2). Slag was also reported, but not in significant amount (Archaeology section 2004, 87). The analysis of grave goods from Ban Bueng Noi was consistent with trends observed in the Upper Mun River Valley, particularly regarding the acquisition and production of craft items. Pottery and iron artefacts were probably manufactured locally, as argued by the petrographic match with local clay sources and the presence of slag respectively (Archaeology section 2004, 85-86). There is no evidence for bronze production on site, but the objects might have been imported through exchange networks (Archaeology section 2004, 86-87). Glass beads were probably acquired in a similar manner. Nonetheless, the local craft productions need to be reassessed as no clear workshop or domestic contexts have been identified.

Figure 6.11 Examples of potteries

Figure 6.12 Examples of metal artefacts, for example, iron chisels and spearheads, bronze bell and rings

Figure 6.13 Raw blue glass, glass beads, and semi-precious stone beads

At STH8, two flexed burials were recovered beneath the main iron production layers. Burial 1 (Figure 6.14), which was the only reasonably-conserved individual, was buried with a half bowl covering their head, which is similar to practice observed at Ban Non Wat and Noen U-Loke (O'Reilly 2014, 301). Slag was also found in the same layer, but outside the grave. The grave is dated to the late Iron Age (3^{rd}-4^{th} century AD) supported by the presence of Phimai black pottery (Figure 6.15), the burial custom, and scientific dating of charcoal (see section 7.3.1.1). Some pottery is typologically comparable to those found at the Iron Age moated site of Phum Snay in Cambodia (Akayama 2013; Miyatsuka and Yasuda 2013; O'Reilly *et al*. 2004, 2006). Furthermore, the excavators probably recognised remains of domestic activity as suggested by a thick layer of fauna and sherds together with glass beads, iron fragments, and slag.

Figure 6.14 Burial 1

Figure 6.15 Examples of nearly complete potteries found at STH8

The third activity identified concerns primary iron production, whose remains dominated the sites of KDT2 and STH8. The new radiocarbon dates and the associated datable finds attested their affiliation with the late Iron Age, dismissing the previous proposition of later date (see section 7.3.1.1). The detail of the production remains will be discussed in the next chapter.

The sites presented are classified into three types: cemetery with possible settlement (Ban Bueng Noi), settlement/cemetery/iron production workshop (STH8), and dedicated iron production workshop (KDT2). The functions of the sites conform to contemporary sites in the Upper Mun River Valley where settlement and workshop coexisted (see section 3.3.2.2). The establishment of these sites may link to an expansion of new settlements to occupy diverse environment in order to acquire more resources (see section 3.2).

The material culture can be feasibly linked with other sites in lower Northeast Thailand, particularly in the Upper and Middle Mun River Valleys (Archaeology section 2004, 98), and the south of the *Dângrêk* Mountains, such as Phum Snay. The evidence found clearly suggests Ban Kruat participated in the ongoing exchange networks and regional interaction across the Iron Age of mainland Southeast Asia.

6.3.2 Ban Kruat in the period of the transition (6th-11th century AD)

It is known regionally that, during the late Iron Age, Dvaravati and Khmer cultures can be traced in many Iron Age settlements whose populations adopted these new traditions aforementioned (see section 3.3.3). Unfortunately, evidence in Ban Kruat is too scarce to assert the local presences of these two cultures. Only a single charcoal sample, collected from metallurgical context at STH8 and dated to the 6th century AD, falls into this period (see section 7.3.1.1.3), but there are no associated finds (i.e. Dvaravati or Khmer related artefacts) to confirm this association.

Despite the rarity of contemporary evidence in Ban Kruat, the immediate vicinity already flourished by both cultures (see section 3.3.3.3 for a broader archaeological picture). The trace of the pre-Angkorian Khmer Prince Citrasena (Mahendravarman) is found at Tham Pet Thong, approximately 45km west of Ban Kruat, dated to the 6th century AD (Fine Arts Department 1986; Srisuchat 1988, 114-115). In contrast, the settlements, such as Ban Pa Khiep, Phu Phra Angkhan, and Ban Fhai, yields evidence associated with the Dvaravati traditions (e.g. carinated pottery, *sema* standing stone, and Dvaravati-style

Buddha images) (Diskul 1995; Srisuchat 1988; Visitchanakun 1999). The cultural interaction between these two cultures is also seen in a hoard of Prakhon Chai bronzes (see section 3.3.3.3).

6.3.3 The Angkorian occupation in the 11th-13th century AD

Chapter 3 discussed the reappearance of the Khmer elites in lower Northeast Thailand as early as the 9th century AD (see section 3.3.4.1.1). Its trace is identifiable at the mountains of Phnom Rung and Khao Plai Bat, 15-20km northwest of Ban Kruat. The early temples, which were probably constructed in the 10th century AD, transformed the mountains into sacred places (Jacques and Lafond 2007, 216; Jumprom 2005, 42-43; Office of Archaeology 2005, 113). Archaeological surveys confirms that the base of the Phnom Rung Mountain had been continuously occupied since the Iron Age and was probably in contact with contemporary communities in Ban Kruat (Jumprom 2005; Office of Archaeology 2005).

Although the Khmers had been active in the vicinity of Ban Kruat around the 10th century AD, there was no firm evidence for Khmer activities in Ban Kruat until the 11th century AD when two Khmer temples (Prasat Thong and Bai Baek), ceramic workshops, and sandstone quarry appeared (Lertlum *et al.* 2008; Prommanoj 1989; Srisuchat 1988, 116-119; Tanlasanawong 2007) (Figure 6.16). According to current evidence, production seems to have been the major activity in this area.

The first production activity to be discussed is that of ceramics. In Ban Kruat, 36-40 mounds of ceramic debris, likely to be the remains of ceramic kilns, present one of the greatest concentrations of kiln sites outside the political core area (Lertlum *et al.* 2008, 31; Prommanoj 1989) (see section 3.3.4.2.3). They were principally grouped into eight clusters located to the east of Prasat Thong which was probably a centre of this community (Prommanoj 1989, 29). All sites were preferentially located close to streams, mostly less than 400-500m. However, only Nai Chian kiln was radiometrically dated which placed the operation between the 11th-13th centuries AD (Thammapreechakorn 2009, 46-47; cf. Prommanoj 1989, 90), but it is still unclear to what extent other kilns operated simultaneously or successively within the 200 years production window. Thammapreechakorn (2009, 170) proposed that the high refractoriness of the clay might have been one factor encouraging the selection of Ban Kruat to base the industry. The Khmer ceramics produced at this locale were probably circulated mainly in the western territories (see section 3.3.4.2.3).

Iron production is another crucial industry found in significant association with locally rich Angkorian evidence. However, with the current data, it has been impossible to conclusively attribute the deposits/workshops to the particular periods. Some sites at least were possibly contemporary to this period as suggested by surface finds (see section 7.3.1.3). The technological examination of metallurgical remains will hopefully help to clarify this issue.

Quarrying rock (sandstone and laterite) was important for Angkorian construction, as discussed in Chapter 3 (see section 3.3.4.2.3). It has been suggested by various related studies that sandstone was likely procured from nearby outcrops (see section 6.2). Laterite, although no evidence for quarrying has hitherto been found, is also assumed to have been exploited locally.

Figure 6.16 Angkorian Khmer sites in Ban Kruat

(Clockwise: Prasat Thong, Bi Baek, Quarry and Nai Jaean ceramic kiln)

It is not yet clear why Ban Kruat was established as late as the 11th century AD, in contrast to its neighbours that began to embrace pre-Angkorian Khmer traditions centuries earlier. What could be suggested is Ban Kruat, to some extent, offered economically strategic resources and products that were essential for the state economy.

According to regional archaeology, the emergence of Angkorian settlement in Ban Kruat may be similar to others. It may correspond to the economic growth and territorial expansion campaign, especially during the reign of Suryavarman I (AD1002-1050). The production locale would have been to generate wealth from local resources to economically support Angkor and local Angkorian economy. Following Angkorian settlement pattern (Evans *et al*. 2007, 2013, 12597-12598; Veeraprasert 2002, 207-208), temples, such as Prasat Thong, Bai Baek, Khok Yang, and Lalom Thom would have been centres of villages/towns in this area.

The rise of the Mahidharapura Dynasty in the 12th century AD, whose origin had a strong relation with lower Northeast Thailand, might have provided a significant boost for local economic activity. Sandstone was needed to construct the elaborate temple complex of Phnom Rung and Muang Tam. The scale of ceramic production might have also been encouraged to expand, together with other kilns in the *Dângrêk* group, in order to supply an increasing demand, as brown glazed ceramics became a commonly used type of ceramics in the empire (Groslier 1981, 28). This was possibly a period when Ban Kruat was fully recognised as a provincial Khmer ceramic production locale stimulating an increase of the number of operating kilns (Thammapreechakorn 2009, 285). According to the temple-based economic model (Hall 2011), it is plausible that Ban Kruat was under an administration of larger settlements (i.e. Muang Tam) and Phimai.

Later in the 13th century AD, the construction of Prasat Thmor, which was part of the network of resthouses on the northwestern route, probably means that Ban Kruat was better connected to other communities. The route was also useful for the distribution and transportation of local products (Lertlum *et al*. 2008, 183, 299-303). The decline of Ban Kruat, as well as its ceramic industry, possibly happened synchronously with the regional deterioration of the Angkorian Khmer authority in the western territories after the reign of Jayavarman VII in the early 13th century AD.

6.4 Summary on the cultural development of Ban Kruat

The review above demonstrates that Ban Kruat shared to a large extent the environmental and socio-cultural features observed in the broader lower Northeast Thailand. The environmental and geographical settings of Ban Kruat enabled and facilitated a long occupation period during which Ban Kruat was an active element of regional cultural development. For the Angkorian period, the evidence is clear in showing that the Khmers extensively exploited resources in Ban Kruat in which would be channelled to support local and regional centres as well as Angkor.

Socio-culturally, it is seen that Ban Kruat is dominated by the Angkorian evidence, whereas the Iron Age is only represented by three sites. The picture of the Iron Age in Ban Kruat has been fortified by the chronological reassessment of the recently excavated archaeological sites of KDT2 and STH8. While KDT2 probably functioned solely as a production site, STH8 was a multi–purpose site for burying the deceased, dwelling, and producing iron.

The early historic period seems to remain ill-defined due to the lack of firm supporting evidence. The picture of Ban Kruat becomes significantly clear in the 11th century AD when the Khmer Empire started to occupy the region. Evidence suggests that the Khmer traditions flourished in Ban Kruat at the same time as in other areas of lower Northeast Thailand. Interestingly, the site became part of the *Dângrêk* ceramic industry. Economic activities is likely to have boomed for this part of Thailand during the periods when the Mahidrapura royal family was enthroned and the improvement of northwestern route, which helped the flow of the products even further.

The archaeological information available is useful to place local iron production into a chronological framework. However, interpretation remains problematic as previous research in Ban Kruat rarely tackled the issues of organisation of production. It will therefore be necessary to consider the archaeology of the broader region, where these topics are better understood, to contextualise and discuss the data present here.

Chapter 7 Iron slag deposits in Ban Kruat: descriptions, proposed dates, and preliminary observations

7.1 Introduction

Prior to the visit by LARP in 2005, metallurgical remains in Ban Kruat had been visited twice, in 1987 (Chandavij and Chandavij 1989) and 1989-1991 (Chaikulchit 1997; Nitta 1991, 1997). These early visits ascribed the Ban Khao Din Tai and Ban Sai Tho8 South mounds to iron production, but no detailed investigations were made. Both studies dated this evidence to "ancient periods", which is quite common in documenting metallurgical sites without datable finds associated.

Ban Kruat slag mounds were subsequently left untouched, but, according to many landowners, many mounds had been demolished between 1950-1980 to make way for agriculture and habitation. The most extensive surveys that generated much information regarding local metallurgical remains took place during 2005-2007 conducted by LARP. The surveys covered 140km^2 in Ban Kruat, which mapped 67 slag mounds sitting alongside Angkorian ceramic mounds and buildings (Sampaongern 2005-2006; Lertlum *et al*. 2008, 47) (see section 6.3). This observation prompted the idea of this metallurgical evidence being likely associated with the Angkorian period (Lertlum *et al*. 2008, 56).

The slag mounds were grouped into nine clusters associated to the villages where they were located (Lertlum *et al*. 2008, 40-55) (Figure 7.1). They were as follows:

1. Ban Khao Din Tai – 11 mounds
2. Ban Kruat – 12 mounds
3. Ban Nong Ian – one mound
4. Ban Khok Yang – six mounds
5. Ban Nong Chik – 10 mounds
6. Ban Sai Tho2 South – two mounds
7. Ban Sai Tho8 South 1 – 12 mounds
8. Ban Sai Tho8 South 2 – seven mounds
9. Ban Sai Tho10 North – six mounds

Slag mounds mostly concentrated in Ban Nong Chik, Ban Khao Din Tai, Ban Kruat, and Ban Sai Tho8 south (Lertlum *et al*. 2008, 52). As a matter of fact, this area contains the highest concentration of slag deposits recorded anywhere in Thailand. Three different site distribution patterns were revealed. The Ban Kruat cluster was the only one found parallel to a nearby stream, whereas Ban Khao Din Tai, Ban Sai Tho8 South, and Ban Sai Tho10 clusters were formed in circles. Ban Nong Ian, Ban Khok Yang, and Ban Nong Chik were of a random distribution (Lertlum *et al*. 2008, 51). A common feature among the sites was a close proximity to streams was a preferable location for the workshops, both iron and ceramic, mostly less than 1km distant (Lertlum *et al*. 2008, 55) and at elevations between 170-210m (Lertlum *et al*. 2008, 53) (Figure 7.1). This might be for the ease of accessing water supply and transportation in addition to land routes (Lertlum *et al*. 2008, 56). While both production activities are in the same area, they are generally segregated spatially from each other (Figure 7.3).

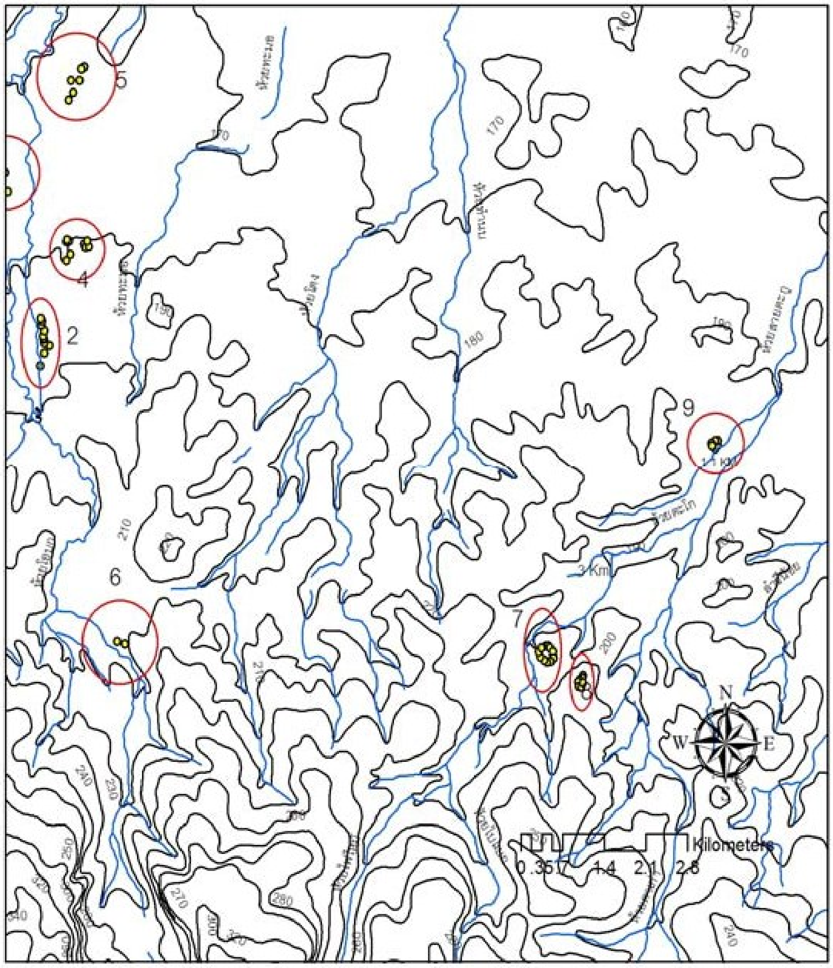


Figure 7.1 Eight of nine clusters of slag mounds documented by LARP

(Image: Lertlum *et al*. 2008, 49)

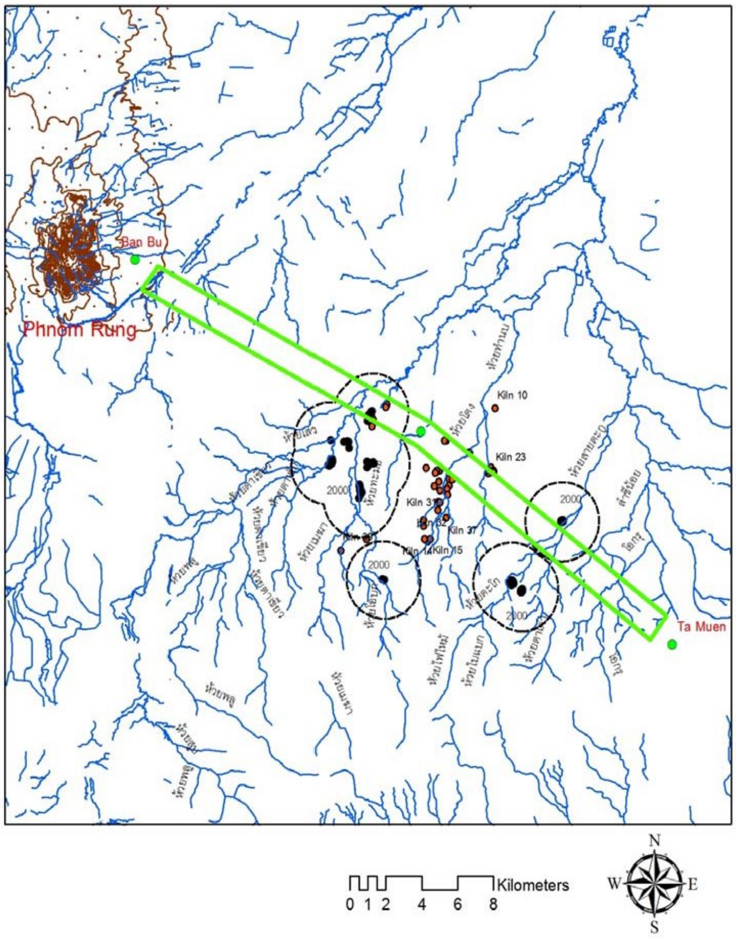


Figure 7.2 The locations of slag mounds surveyed in relation to Angkorian northwestern route (green line) and local water network. Slag and Angkorian ceramic deposits (kiln) are marked by black and red dots respectively.

(Image: Lertlum *et al*. 2008, 57)

Based on this spatial relationship between the ceramic production remains that were unquestionably Angkorian and the other production remains, the project posited an important role of Ban Kruat as an extensive production zone for iron, ceramic, and stone, possibly for Angkorian settlements. The team went further to excavate two selected iron slag mounds (KDT2 and STH8) to elucidate the site formation and iron technology practised (see section 7.2.4 and 7.2.7). The project unveiled fundamental information regarding the site, activities, and the relationship between them and the cultural and environmental landscape (Im and Lertlum 2015; Lertlum *et al.* 2008, 2010; Tanlasanawong *et al.* 2007). A more detailed technological reconstruction was proposed as a subsequent part of the project, and the current thesis represents a step in that direction (Venunan 2011; Yoopom 2010).

Our knowledge derived from these prior studies is largely limited to two excavated sites. Considering the significance of the area and its metallurgical remains, slag deposits have a potential to unravel more information on the technology and its organisation and economic history. However, this required a reassessment of both old and new archaeological assemblages, as well as a dating programme in order to better integrate Ban Kruat iron production into the broader archaeological landscape.

7.2 Nine clusters of slag deposits

The survey and sample selection strategy have been discussed in Chapter 5. The visit could confirm 47 slag deposits from 67 sites reported previously (Figure 7.3 and 7.4) (see Appendix C and D). The decrease in the number of the sites is probably because of a re-definition of the sites by the author. This 2012 survey also found most deposits disturbed to various degrees by modern activities (habitation and agriculture) causing them to partially or completely lose their original shape. Accordingly, some sites previously recorded in 2005-2006 might have been destroyed or flattened, thus, were not identified by the author. This mentioned disturbance consequently made the original size of the mounds very difficult to estimate.

Information obtained from all deposits was used for overall characterisation; however, the collections sampled from those available on the surface of 24 sites were visually examined in more detail, with the hope to obtain a general idea about patterns and differences in the nature of the remains. The entire collections from the excavated sites were also fully reinvestigated, in combination with the information derived from prior studies (Chuenpee *et al*. 2014; Venunan 2011; Yoopom 2010). Of these 24 sites, 12 sites were selected for laboratory-based analyses (see in section 5.1.2 for site selection criteria and Appendix D).

In the following section, the information about each cluster, including the current condition, any noteworthy features, and the sites selected for the laboratory analysis is given. Metallurgical remains found and collected for examination are discussed in separate sections (see section 7.3.2).

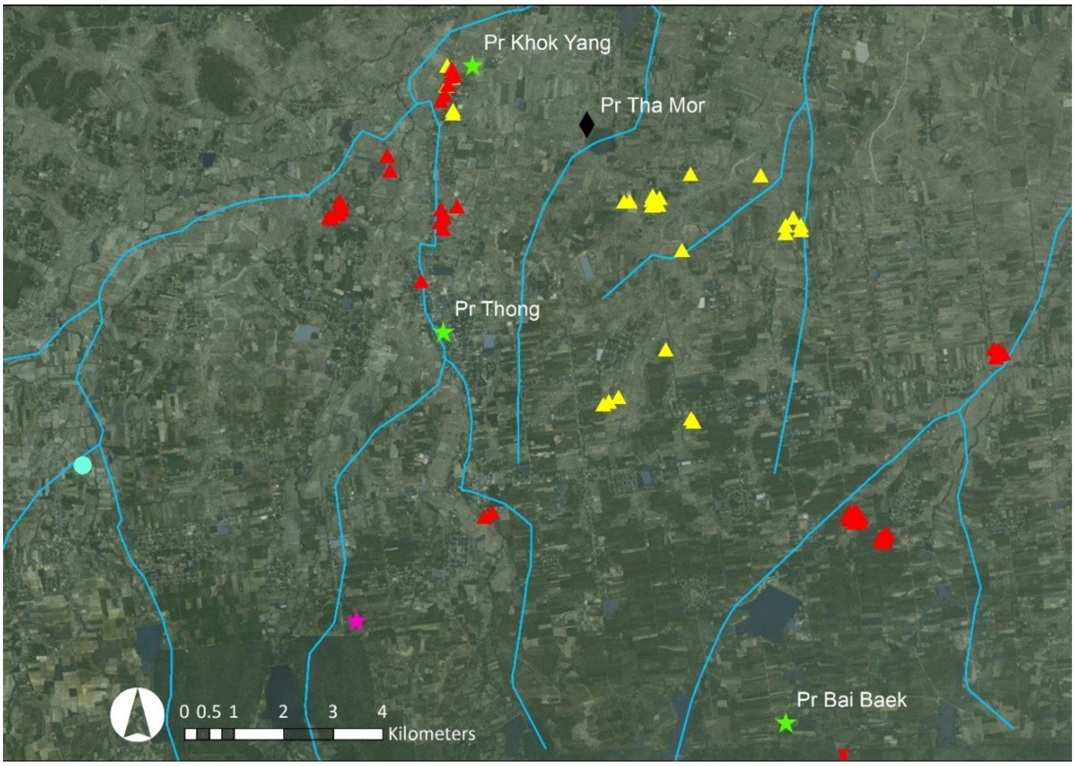


Figure 7.3 Map shows the metallurgical sites (red triangles) in association with the Iron Age Ban Bueng Noi (blue dot), Angkorian temples (green stars), Angkorian resthouse (black diamond), Angkorian ceramic mounds (yellow triangles), Angkorian quarry (purple star), and mountain passes (red pins).

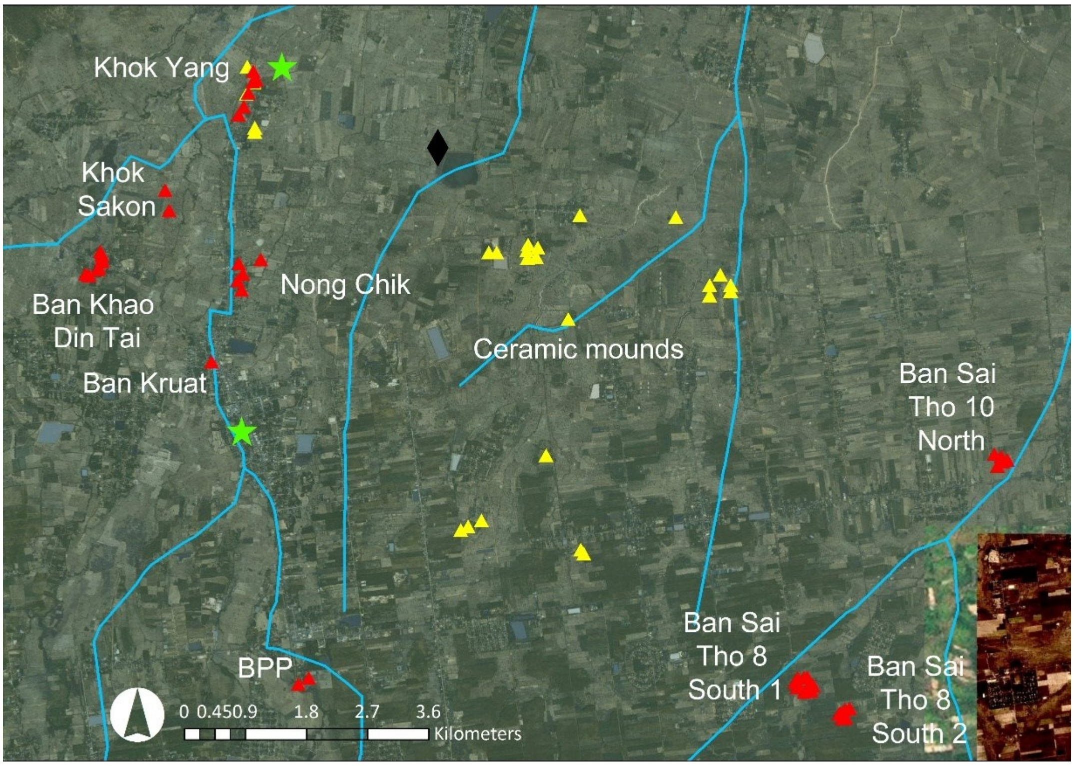


Figure 7.4 Map shows a distribution of the metallurgical sites and ceramic mounds

7.2.1 Khok Yang (KY)

This cluster is located in the northernmost part among the nine slag clusters. Six slag deposits near the ceramic kiln were spotted (Figure 7.5); however, only two locations still preserved their mound shape (the mound KY5 and KY6) (Figure 7.6) with a slight disturbance from the modern activities, especially agriculture. The rest of them were already demolished to make way for agriculture and buildings.

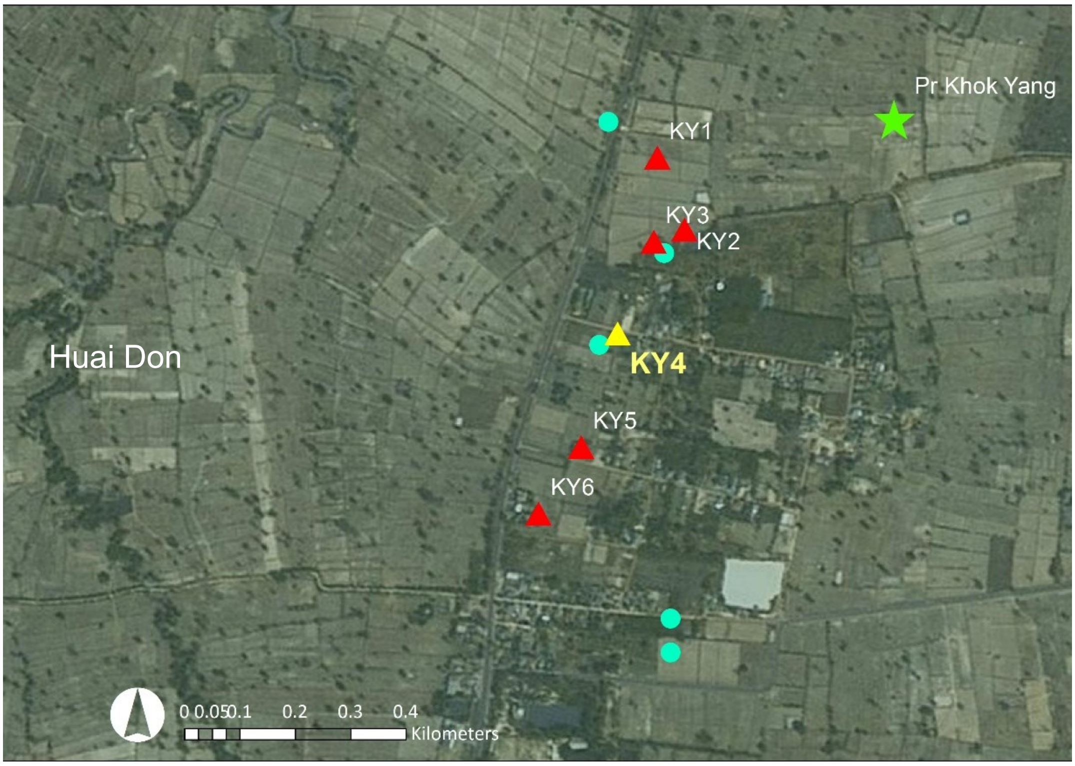


Figure 7.5 A map shows the location of six slag deposits (KY1-6), ceramic kilns (blue circles), Prasat Khok Yang, and Huai Don. The site selected for analysis is marked by the yellow symbol.

Khok Yang has been so far one of two locations where both metallurgical and ceramic productions were recorded in the same area. A small local Khmer temple, Prasat Khok Yang, was once standing to the east of slag concentrating areas.

Slag samples were collected from the surface of the mound KY4 (sugarcane farm) (Figure 7.8). More complete mounds (KY5 and 6) were not selected as there were few metallurgical remains available on the surface compared to the chosen mound.

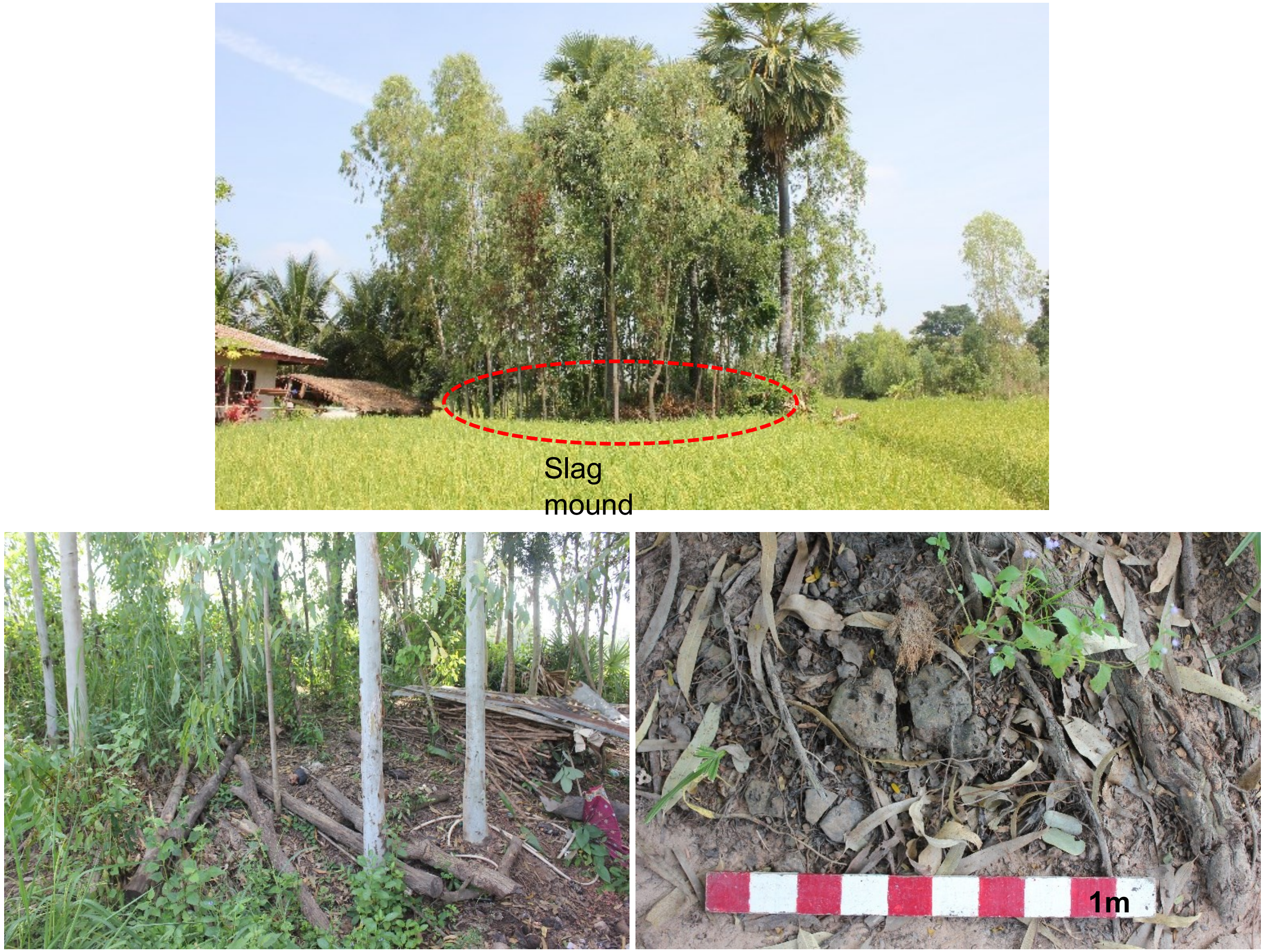


Figure 7.6 Mound KY5, one of preserved slag mounds in Khok Yang

Figure 7.7 An Angkorian Khmer ceramic mound and sherds distributed on the surface

Figure 7.8 View of the mound KY 4. Slag samples were retrieved from the ground marked by a dashed line box, which is difficult to see due to overgrown sugarcane.

7.2.2 Nong Chik (NC)

This cluster is situated south of Khok Yang. Five slag deposits were documented (Figure 7.9), but no complete mounds were recognised. Like Khok Yang, here ceramic and iron production co-existed seen at the mound NC4. This mound constituted the most interesting feature of a large partially flattened slag mound of approximately 4-5m wide, 8m long, and 1.5m high lying next to a similar-sized mound of Khmer ceramics (Figure 7.10). Two large slag blocks were found at this deposit (Figure 7.11). This group of slag is considered rare in Ban Kruat for only six of them were found in NC, KDT2, STH8, and STH8/2. All blocks found in Ban Kruat share to some extent similar large sizes and heavy weights, except the KDT2 one, which is obviously different from typical slag lumps that are commonly associated with all deposits. In brief, they are much larger and very heavy, have rough surface and probable conical shape, and look like the accumulation with porosities in between. A full discussion on them is made in the separate section (see section 7.3.2).

Slag samples were selected from the mound NC4 due to its spatial relationship with the ceramic mound and in hope that they may have represented Angkorian ironmaking activity. The technological tradition, if found different from the Iron Age tradition, may address this question. A small piece from the slag block was selected in addition to smaller slag lumps available on the surface from this spot.

Figure 7.9 The cluster of Ban Nong Chik slag deposits. The site selected for analysis is marked by the yellow symbol.

Figure 7.10 The site of NC4 (behind a person) and slag fragments on the surface.

Figure 7.11 Large slag blocks found near a slag mound. The block in the upper image is approximately 48cm long, 39cm wide, and 40cm high, while the other one is approximately 88cm long, 78cm wide, and 35cm high. A small sample was retrieved from the slag block shown in the below image.

7.2.3 Ban Khok Sakon (KSK)

This small cluster of three slag deposits was discovered almost 2km Northeast of Ban Khao Din Tai cluster in the 2005 survey (Chaiya 2007; Sampaongern 2005-2006); however, 2012 work confirmed only two of them (KSK1 and 2) (Figure 7.12).

The mound KSK1 was chosen as it offered more slag samples to be collected. It is a small mound, located next to a sugarcane field, where slag could only be seen in the profile. The survey could not confirm to which extent this mound might have been a result of metallurgical activity or of the preparation for surrounding agricultural lands that eventually formed a mound. Slag was, however, not found spreading deeply into the sugarcane farm, next to the mound; therefore, it is quite likely that it is an original slag mound (Figure 7.13).

Figure 7.12 The location of Khok Sakon situated on the left of Huai Don (right). The site selected for analysis is marked by the yellow symbol.

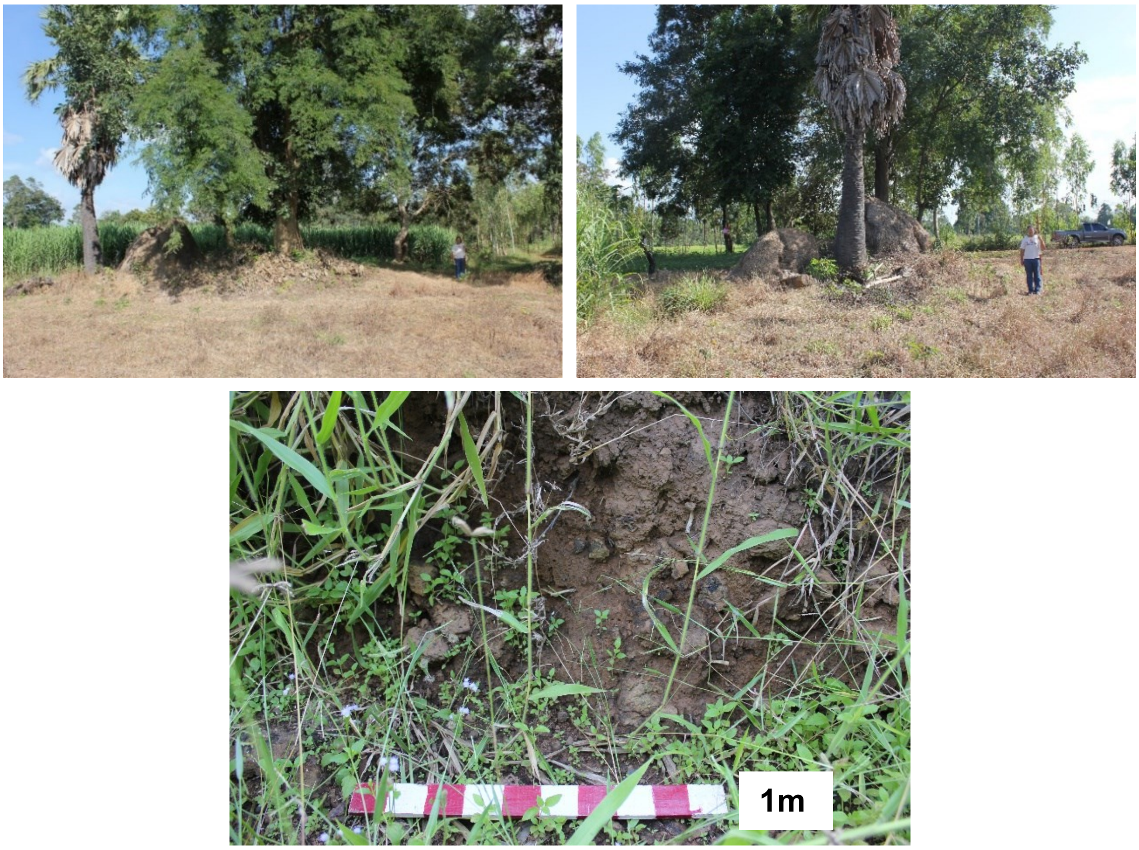


Figure 7.13 The site of KSK 1 and slag fragments revealed in the mound profile

7.2.4 Ban Khao Din Tai (KDT)

A series of eight large slag mounds or deposits was recorded within this village (Figure 7.14). The only complete slag mound (KDT2) could be measured to the size of approximately 7m high and 50m in diameter (Yoopom 2010, 33), whereas the others have lost their original shapes. Based on the appearance of those preserved, however, it can be argued that some mounds, such as the mound KDT1, 3, and 7 might have been of comparable size.

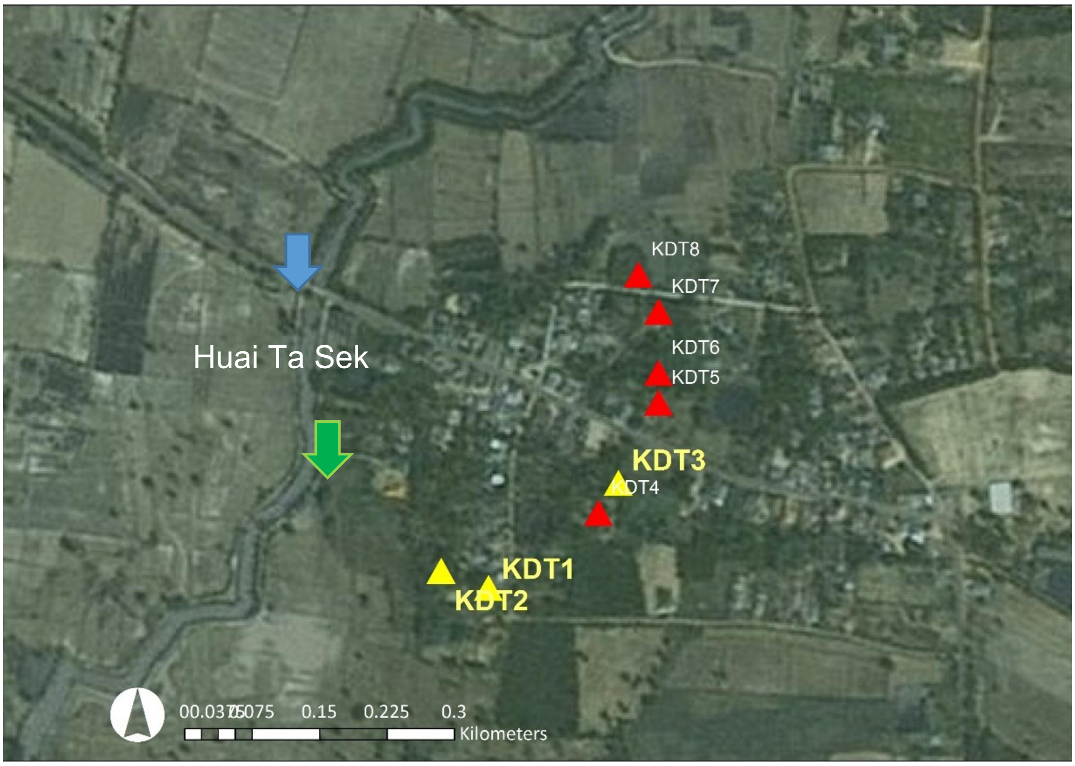


Figure 7.14 The distribution of Ban Khao Din Tai slag deposits. Huai Ta Sek is on the right. The sites selected for analysis are marked by yellow symbols. Two arrows indicate the locations where clay samples were collected (blue – KDTTS and green – KDTRF)

Modern destruction processes, while obviously unfortunate, allow us an insight into how some of these mounds were formed, particular the mound KDT1 which shows how it was formed exclusively by the accumulation of metallurgical waste and geological materials (Figure 7.15). Besides waste from iron production, ceramic fragments of domestic and Khmer types were also recorded at the mound KDT7; these suggest that this site might have been related to the Angkorian Khmer period.

Figure 7.15 Images show the profile of KDT 1 allowing insight into its formation which is similar to what described by the excavation at the mound KDT2.

Among all deposits approached, this cluster received most attention as LARP decided to excavate one of its mounds, KDT 2, as one of the few complete slag mounds in Ban Kruat and taken as representative (Lertlum *et al*. 2008, 116-183 (Figure 7.16). The main objective was to achieve a fuller understanding of the site formation and production activities conducted.

Figure 7.16 Overview image of the site of Ban Khao Din Tai (KDT 2). The upper images show the mound as it is looked from the west.

7.2.4.1 The 2007-2008 LARP excavations at KDT 2 and previous technological reconstruction

The excavation took place over two one-month seasons during 2007 and 2008, under the direction of the LARP archaeology team, including the author. As a full report of the excavation has already been mentioned elsewhere (Lertlum *et al*. 2008, 116-183; Yoopom 2010), this following section concentrates on the metallurgical evidence together with previous archaeometallurgical studies on this site (Chuenpee *et al*. 2014; Venunan 2011; Yoopom 2010). Findings and hypotheses are summarised as presented in previous works, before addressing them more critically based on the new observations and analyses by this PhD's author.

The excavations in two trenches, at the centre and the edge of the mound, revealed two separate areas dedicated to specific purposes: the smelting area at the centre and the dumping area at the slope (Figure 7.17). Within a 3.5m deep archaeological layer, the team discovered ten furnace remnants (Figure 7.18 and 7.19) and abundant metallurgy-related evidence. Evidence unearthed covered almost all components involving an extractive metallurgy including two types of slag (Figure 7.20), large fused slag (Figure 7.83), tuyères (Figure 7.21), clay plugs (Figure 7.22), furnace fragments (Figure 7.23), and laterite fragments, possibly the ore used (Figure 7.24). Besides an almost complete set of smelting components, at least eight working floors were identified. They were in the form of hardened clay layers associated with furnaces (Figure 7.18 and 7.19). These floors, combined with the furnace remains, suggested a preparation of each operational episode (Figure 7.25). No indications of sedimentation or production activities being paused were identified, probably suggesting successive activities. Compared to Ban Sai Tho7 (see section 6.3.1), no secure evidence for smithing process was found, but the discovery of the six denser, heavy, relatively convex shaped slag cakes in the furnace 7 may provide a clue for this activity being carried out at this site too (Figure 7.20).

Figure 7.17 Two excavations pits at KDT 2 suggesting a spatial organisation of workshop that smelting activities were conducted at the centre of the mound, while wastes were dumped on the slope.

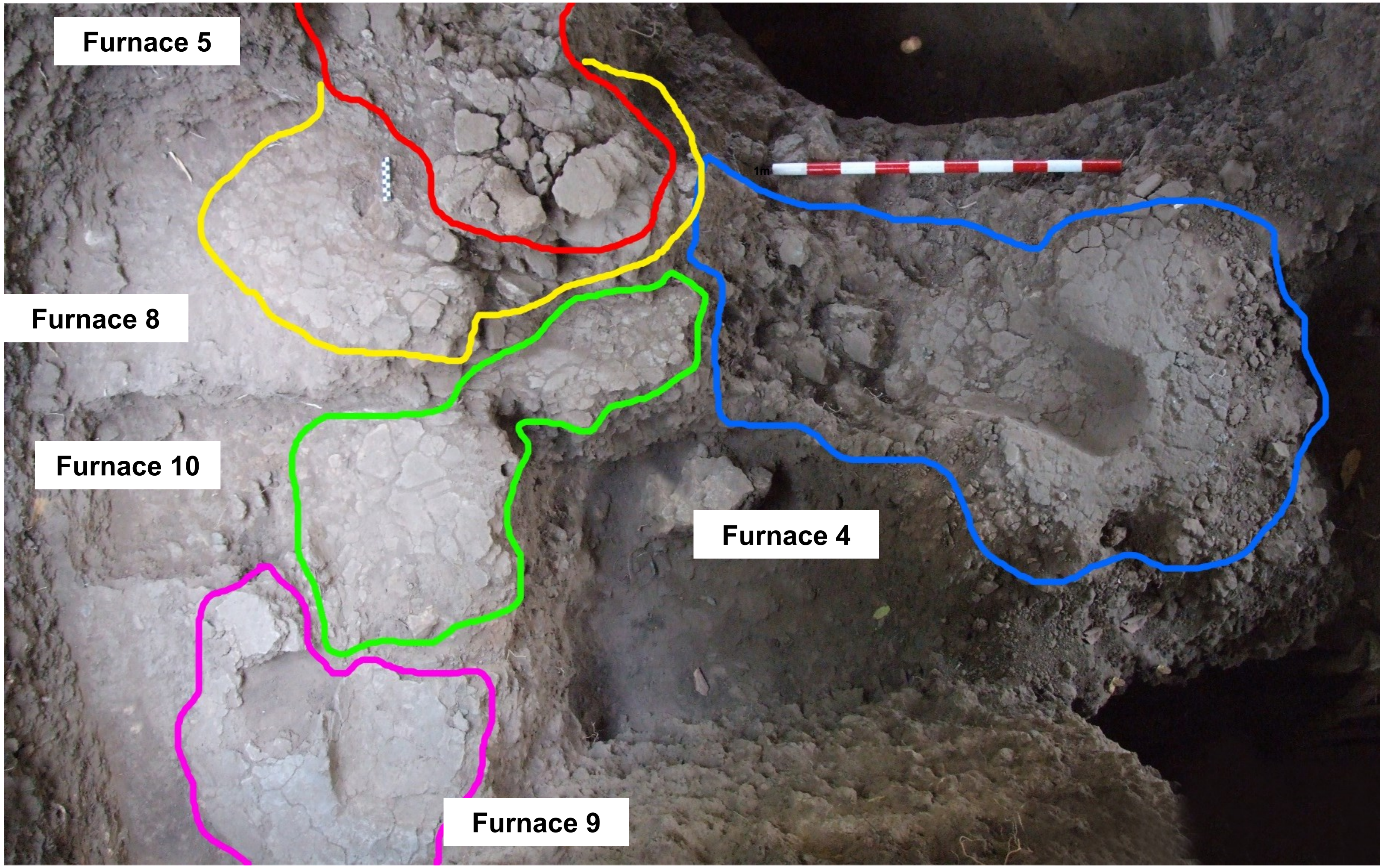


Figure 7.18 Some furnace remains in the test pit 1

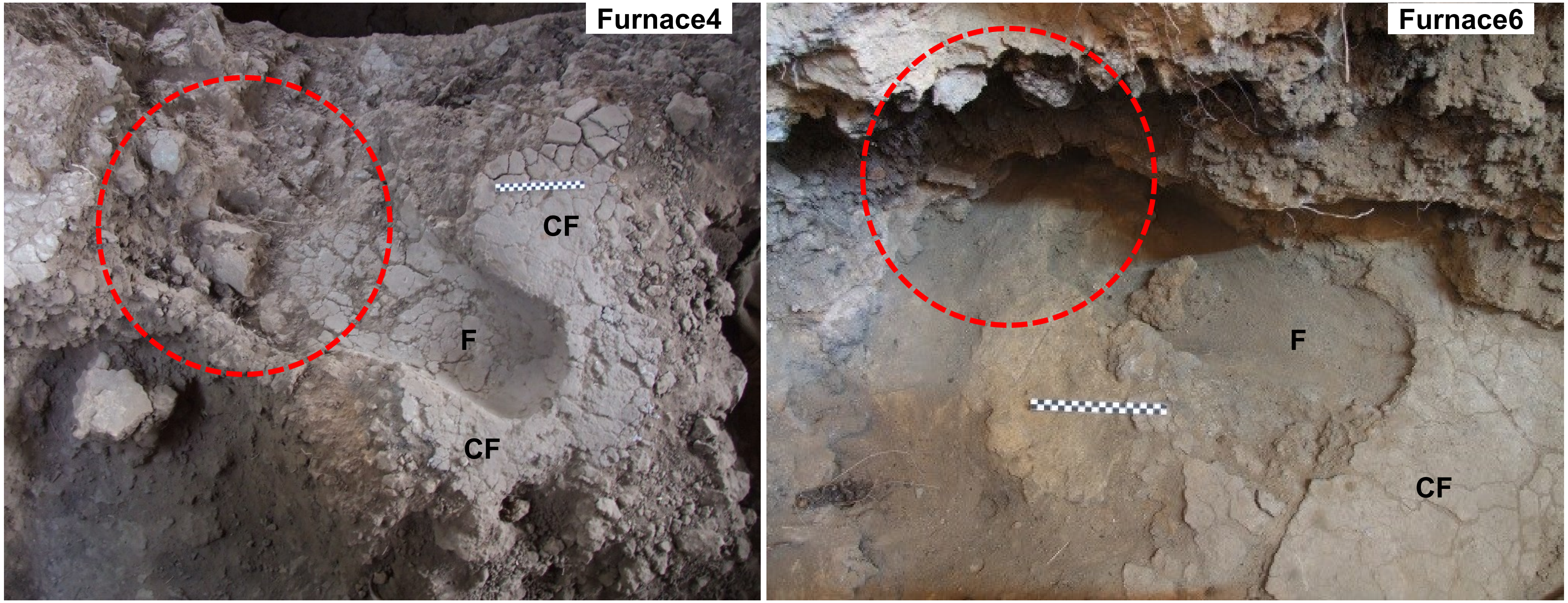


Figure 7.19 Images of some furnace remains uncovered at the site of KDT 2. Notably, the front part (ellipse shape depression) (F) always survives in contrast to the chamber. Clay paved working floors (CF) can be seen in these images. The red dashed lines suggest the area where the chamber may have been.

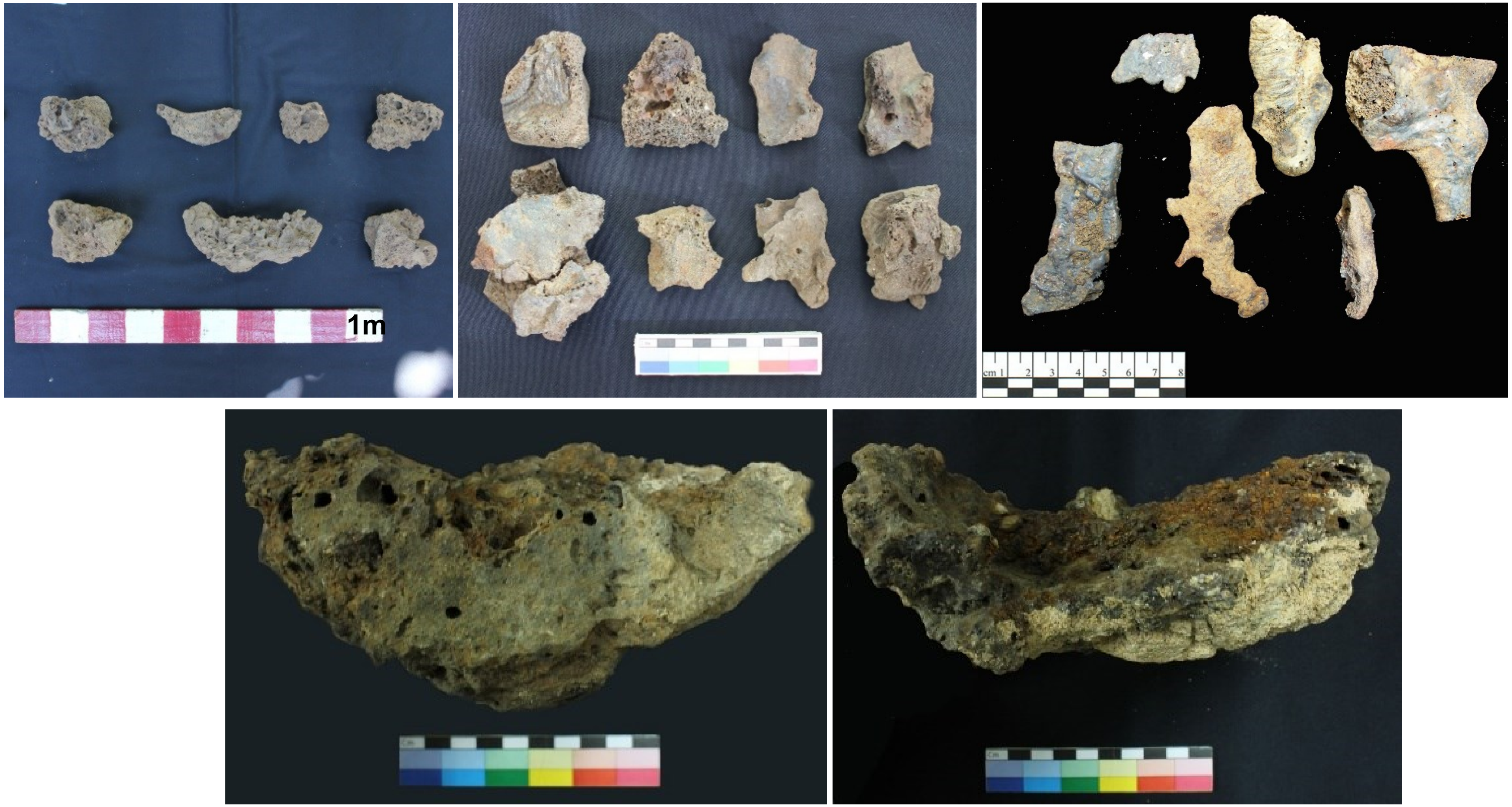


Figure 7.20 Two types of slag found: irregular-shaped slag (upper), which dominates the site and is classified as smelting slag according to previous studies (Chuenpee *et al*. 2014; Venunan 2011) and plano-convex shape, which only six of them were found associated with the furnace 7 (below).

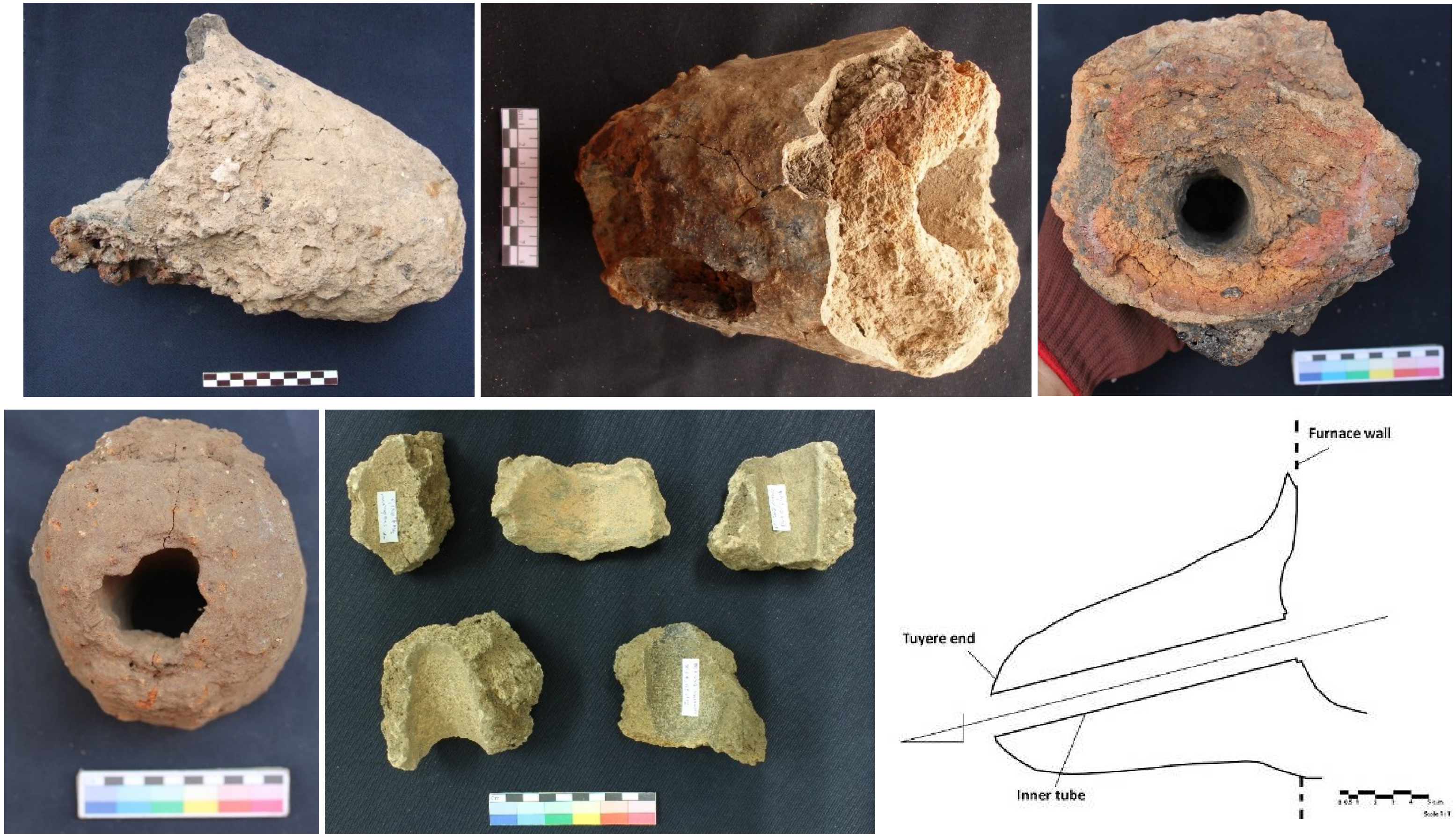


Figure 7.21 Images of tuyères. Though some of them preserve their original shapes, the majority of them were found as fragments.

(Drawing: Yoopom 2010, 103)

Figure 7.22 Images of clay plugs. Like tuyères, the majority of them were found as broken pieces.

Figure 7.23 Examples of furnace fragments

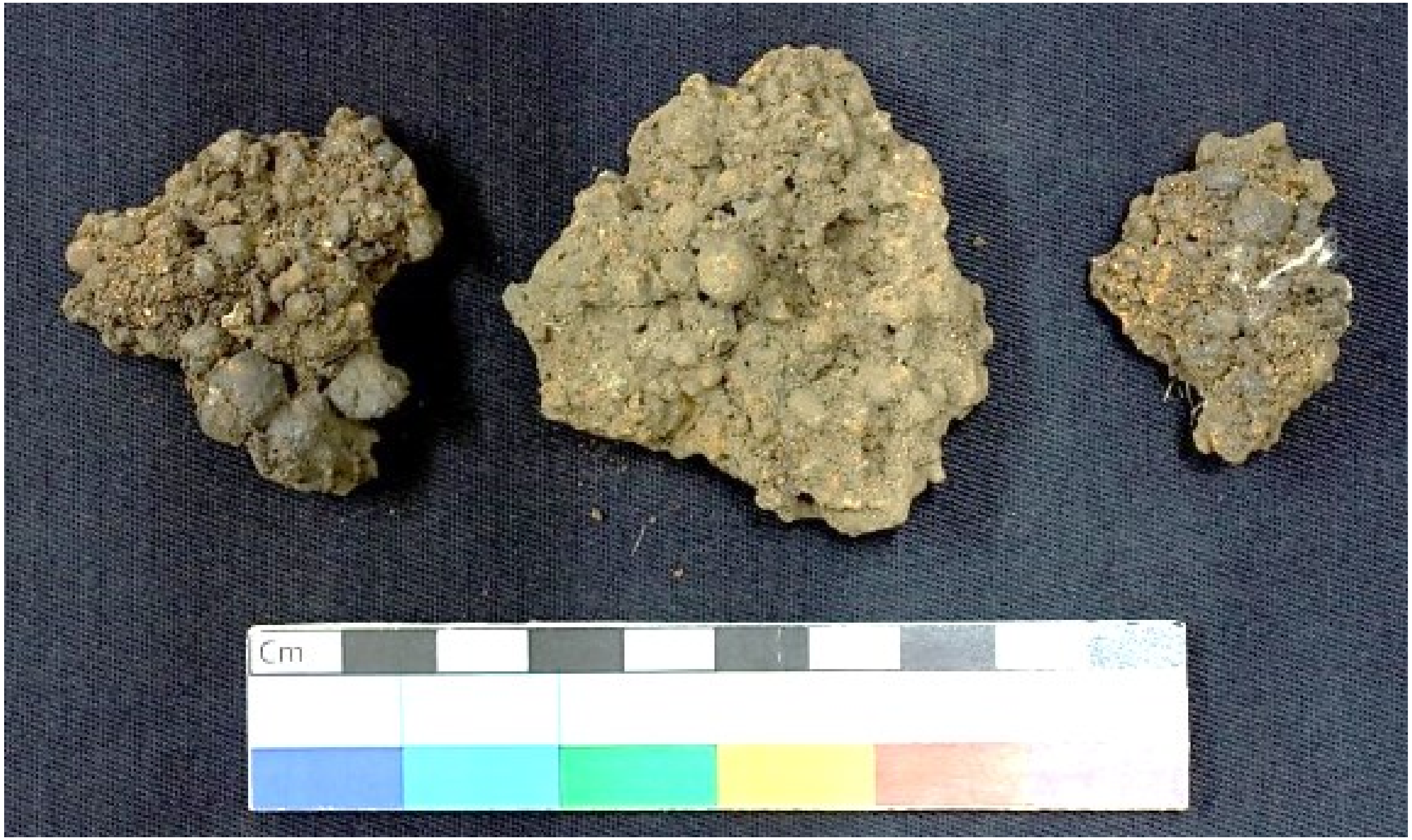


Figure 7.24 Laterite fragments. Only a few of them could be recovered during the excavations.

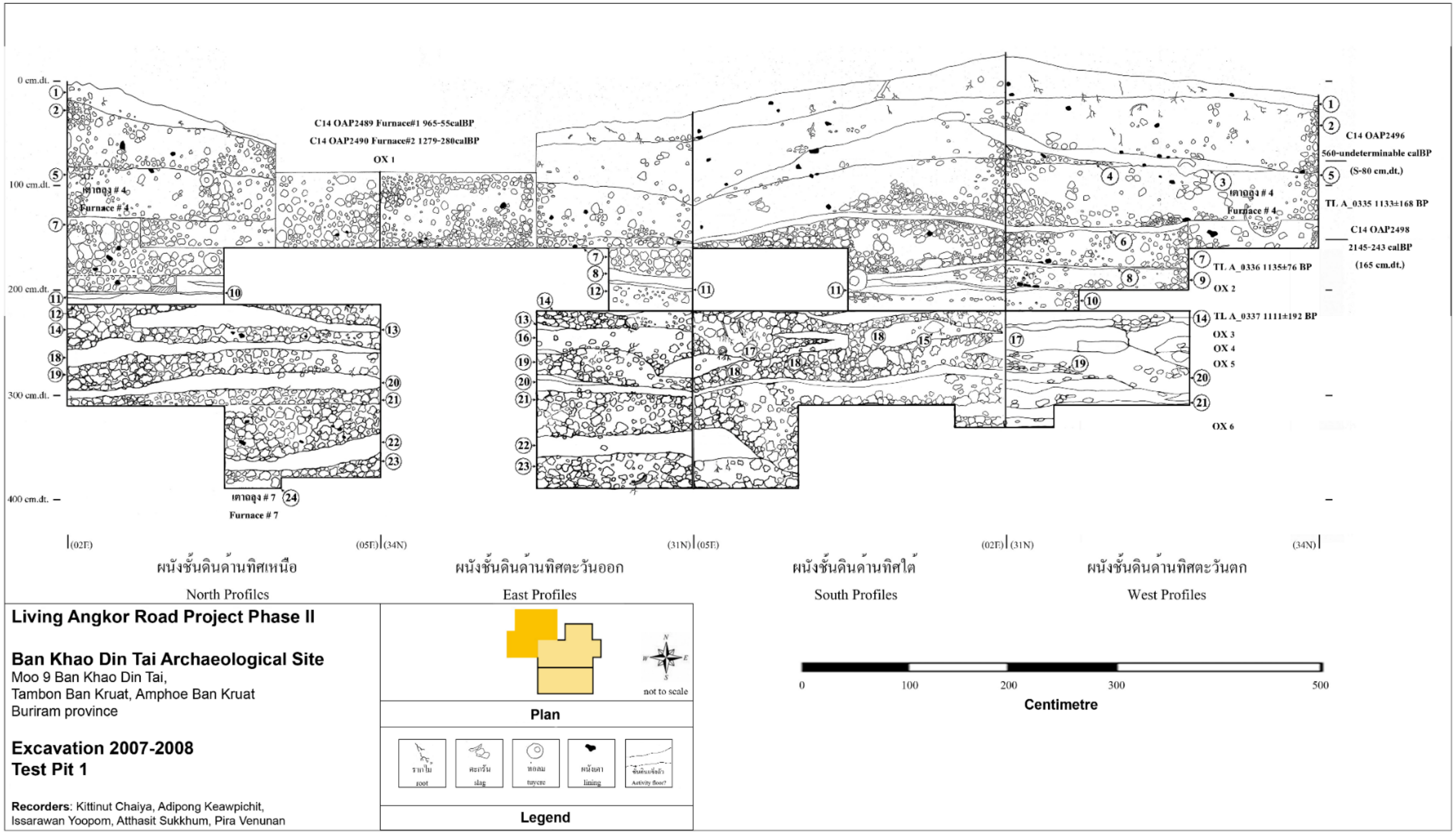


Figure 7.25 Excavation profiles of the test pit 1 at the centre of the mound. The white layers are the working floors mentioned in the text.

(Image: courtesy of the Living Angkor Road project)

Issarawan Yoopom (2010) examined the metallurgical assemblage visually in order to propose an initial reconstruction of the smelting technology. According to her examination, all furnaces were demolished and filled with metallurgical waste. The furnaces were thought to have been pear-shaped in plan and cylindrical shaft type in profile. This reconstruction was based on the furnace remains, in conjunction with the partial reconstruction of the rim and wall parts and wooden features left on the furnace fragments (Yoopom 2010, 98-99) (Figure 7.26). The actual superstructure or the height of this furnace could not be reconstructed, however. The furnace was divided into two parts, but still connected: a forehearth, 70 cm long and 35 cm wide, and a furnace proper of approximately 60-80 cm in diameter (Figure 7.27). The front part was thought to serve as a peep hole or for inserting fuel (Yoopom 2010, 115). The working platform in the form of layers of hardened clay was survive around the furnaces and seen in the stratigraphy. The furnace wall fragments were about 2.4-5cm think, and only a few of them were vitrified.

The tuyères are very robust, unlike those discovered elsewhere (see section 4.3.1.1 and 4.3.2.1) (Figure 7.21). They are very difficult to measure due to their poorly preserved condition. For those that preserve their original form, they are funnel-like with a tapering profile. Bore diameter ranged 4-11cm with slight difference between front and end holes. The microstructural study on a fragment of a tuyère from the furnace 2 inferred that a clay used contained quartz and iron minerals, possibly tempered with rice chaff (Figure 7.28). The structure was quite friable; only external surfaces were more stable than the core part (Yoopom 2010, 103). It was suggested that tuyère(s) would have been attached to a wall at a downward angle (Yoopom 2010, 99). No remains of bellows were found, and the number of tuyères per each furnace remained uncertain as none of them were found in their original locations.

The excavations also recovered a number of distinctive finds shaped like a water drop or similarly oval in shape (Figure 7.22). The team coined the term “clay plug” for this find type, and its function was tentatively interpreted as a block for a slag tapping hole. Like tuyères, the size was not standardised, ranging 20-25cm long and 12-15cm wide (Yoopom 2010, 107). It was clear that one end was completely vitrified, suggesting a direct contact with a high temperature, in contrast to the other terracotta end (Yoopom 2010, 107). Yoopom (2010, 111) suggested that slag tapping hole(s) might have existed, and that although no external slag pits were found near the furnaces, the smelters might have used an elevation difference to force slag to flow out.

Figure 7.26 Wooden features left on furnace fragments

(Left image: Yoopom 2010, 98)

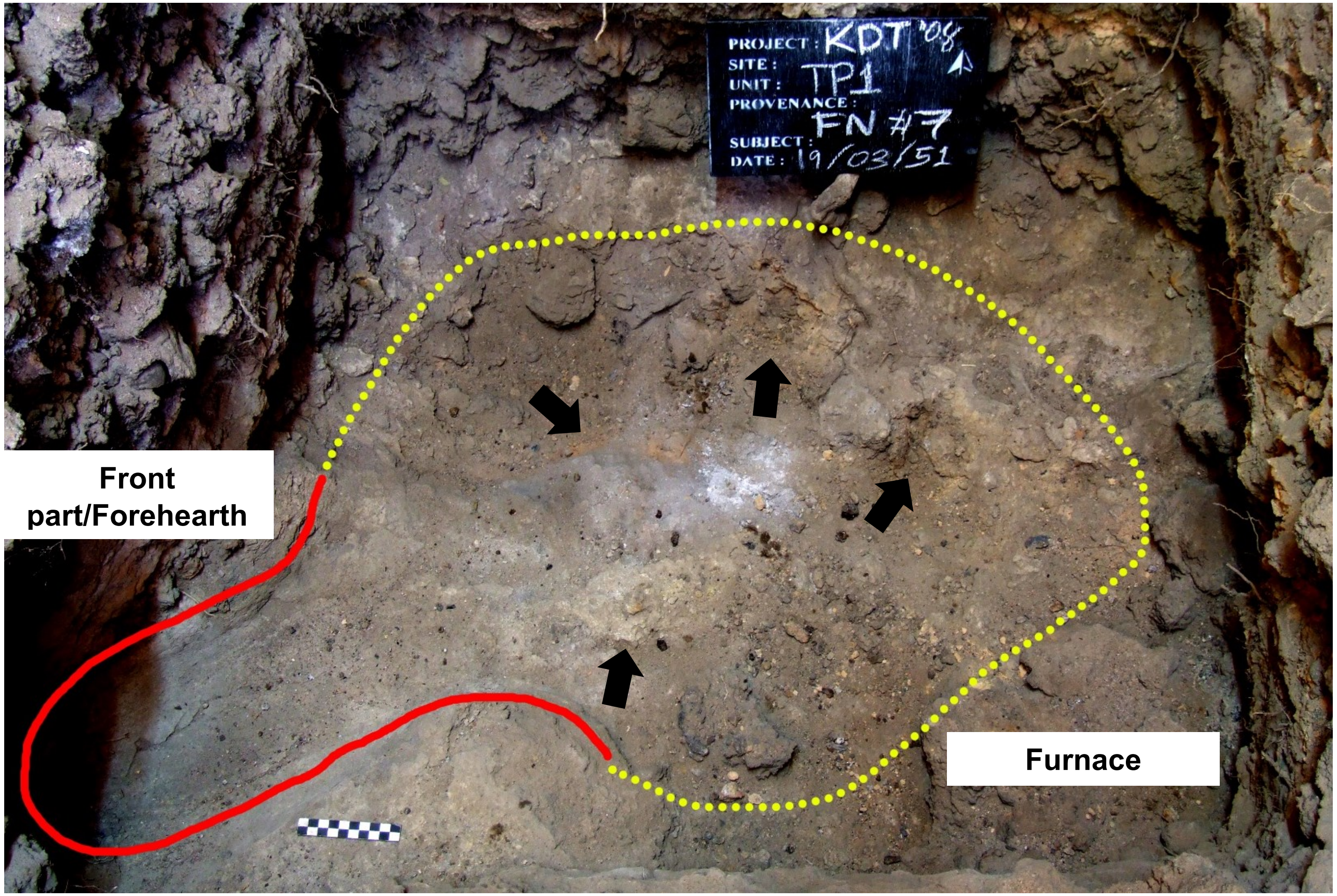


Figure 7.27 Speculation of furnace structure based on an excavation at furnace 7. The existence of the chamber is suggested by the presence of a circle of well-compacted slag, as opposed to dumped slag that are always loose. No lining was observed during the excavation; although, there is fired clay floor identified in the middle of the furnace (black arrows).

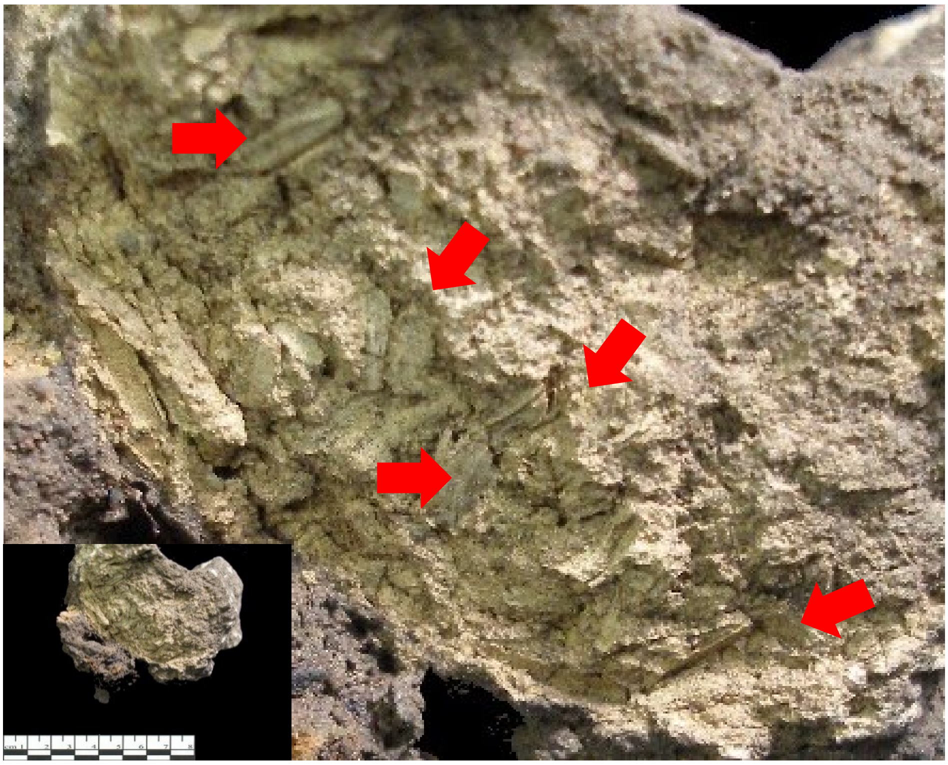


Figure 7.28 Imprints of rice chaff in the body of the tuyère (red arrows)

According to Yoopom (2010), technical ceramics were hand-formed and their shapes and sizes were not standardised. The ore and charcoal are thought to have been locally procured. Laterite were considered a potential ore which is locally abundant; while the charcoal was proposed to be collected from the nearby forest and processed to the size of 1.5-2cm as suggested by charcoal remains (Yoopom 2010, 115) (Figure 7.29).

Figure 7.29 Imprints of charcoal fragments in slag

All evidence considered led Yoopom to that conclusion that a direct smelting process was employed to produce a bloom by smelting laterite in a cylindrical shaft furnace with slag tapping hole(s) (Yoopom 2010, 71-114) (Figure 7.30). The preparation of working floor would have started by levelling with clay the surface that was full of metallurgical wastes from previous operations. The base of the furnace chamber was prepared where the furnace was intended, possibly by digging a depression within a layer of wastes. Then a wooden frame of unknown specie might have been constructed and lined with clay, prior to an initial firing for stabilising the furnace. The charge comprised of laterite and charcoal was inserted, and air was blown into the furnace with bellows. When slag was created or filled to a certain level, it might have been tapped out through a hole. After an undetermined length of time, a bloom would be obtained (Yoopom 2010, 115).

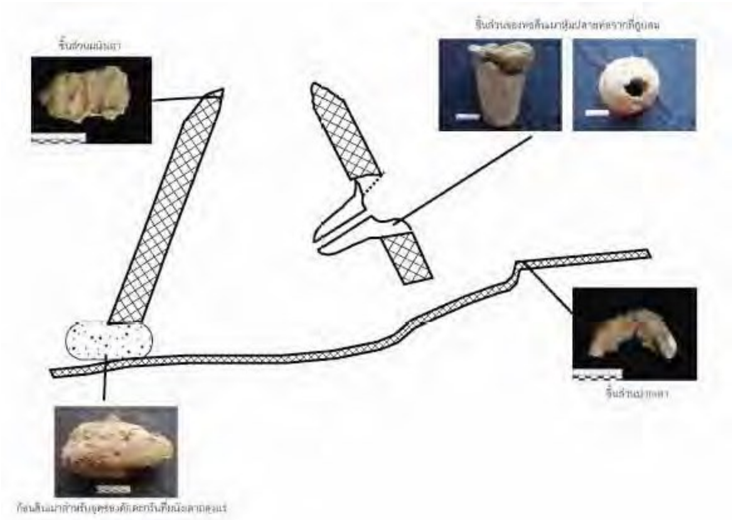


Figure 7.30 Yoopom's reconstruction of Ban Khao Din Tai furnace (2010, 112)

A subsequent laboratory-based archaeometallurgical approach was employed to assess the previous proposal and extract more data to establish a fuller reconstruction (Venunan 2011). Twenty-one samples, studied by scanning electron microscope with X-ray microanalysis and (polarising) energy dispersive X-ray fluorescence spectrometry, included slag, technical ceramics, laterite fragment, and domestic pottery sherds (Venunan 2011, 39-40).

While the findings of this pilot analytical project were largely in agreement with Yoopom's model, some new insights were contributed. The slag samples were shown to be a product of bloomery smelting, and they could be macrostructurally divided into three main groups: dense slag group, semi-porous slag group, and porous group (Figure 7.31). However, these groups did not correspond with distinct mineralogical (Figure 7.32) and chemical features, as most of them were internally quite similar. In addition, they were all characterised by the relatively high bulk alumina levels (approximately 11-14 wt% Al_2O_3) (Figure 7.32) (also see Chuenpee *et al*. 2014), perhaps corresponding with the high alumina levels in the laterite sample (approximately 19 wt% Al_2O_3). The comparison between technical ceramics and domestic pottery suggested that they were made of different fabrics (Venunan 2010).

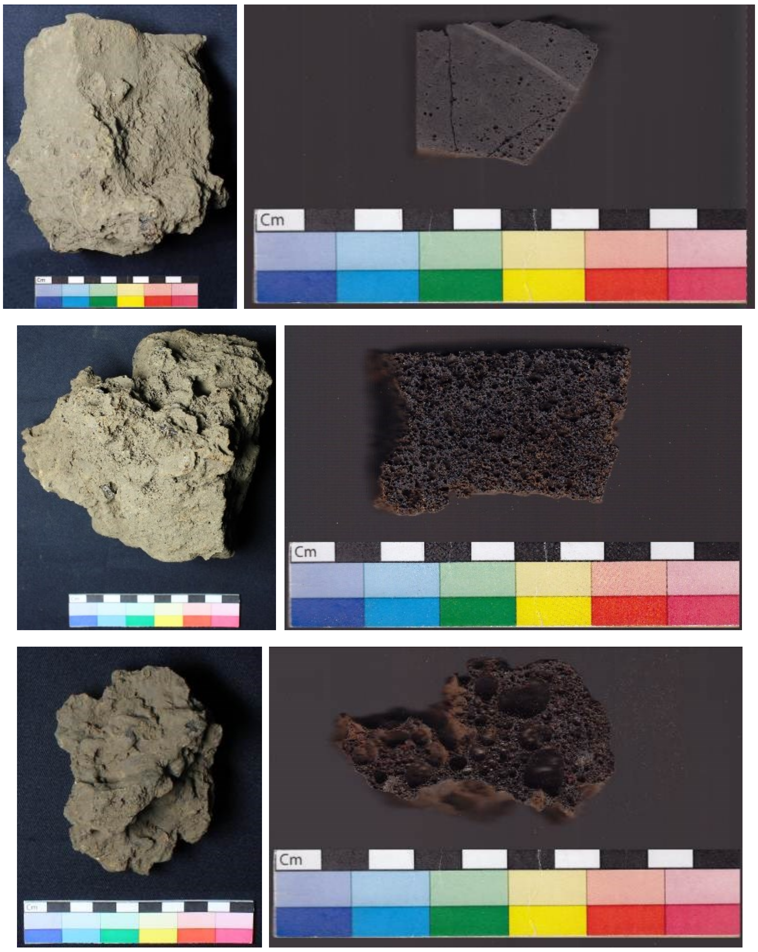


Figure 7.31 Three groups of smelting slag

(Image: Venunan 2011, 53-54)

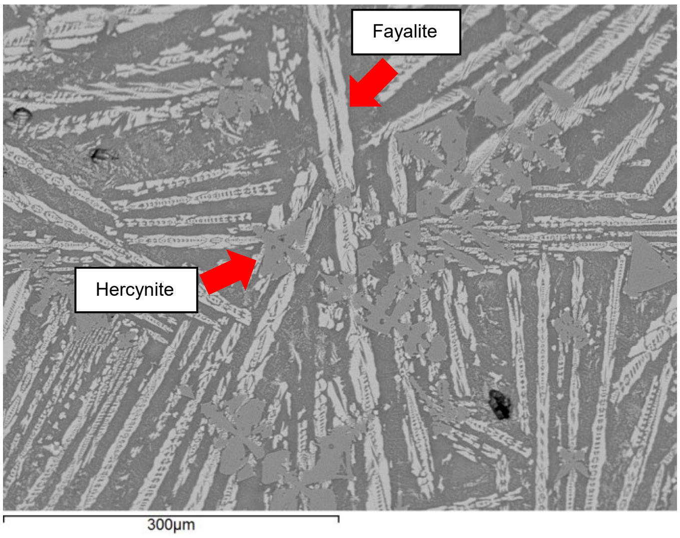


Figure 7.32 BSE image shows a typical microstructure of slag samples studied. The lath-shaped fayalite is indicative of a relatively fast cooling, while the abundance of hercynite is consistent with the high alumina contents.

(Image: Venunan 2011, 56)

Although prior studies have provided useful insight into iron technology practised at KDT2, it should be noted that the small sample size meant that inferences could not be conclusive and needed better clarification, and some questions were left unanswered. To address in more detail the questions raised by these prior studies, the number of samples to be analysed from KDT2 was expanded. As it is the only site excavated, it was based suited to evaluate of technological variability within a single site. Other two slag mounds from the same cluster (KDT1 and 3) were sampled to allow for a comparison between slag deposits within the same cluster, which were deemed to be broadly contemporaneous. A clay sample was also collected from nearby Huai Ta Sek to investigate a possible clay source (Figure 7.33).

Figure 7.33 A clay sample collected from a nearby Huai Ta Sek

7.2.5 Ban Kruat Town Centre (BKT)

This cluster is located within Ban Kruat town centre, where most remains were found under the residential constructions, particularly houses, or in their front yard or backyard (Chaiya 2007) (Figure 7.34). Unfortunately, the 2012 survey only identified one out of the 11 deposits previously documented for it was the only deposit that the author could access. Notably, this cluster is the closest locale to a local temple, Prasat Thong, which was probably the centre of this community during the Angkorian period.

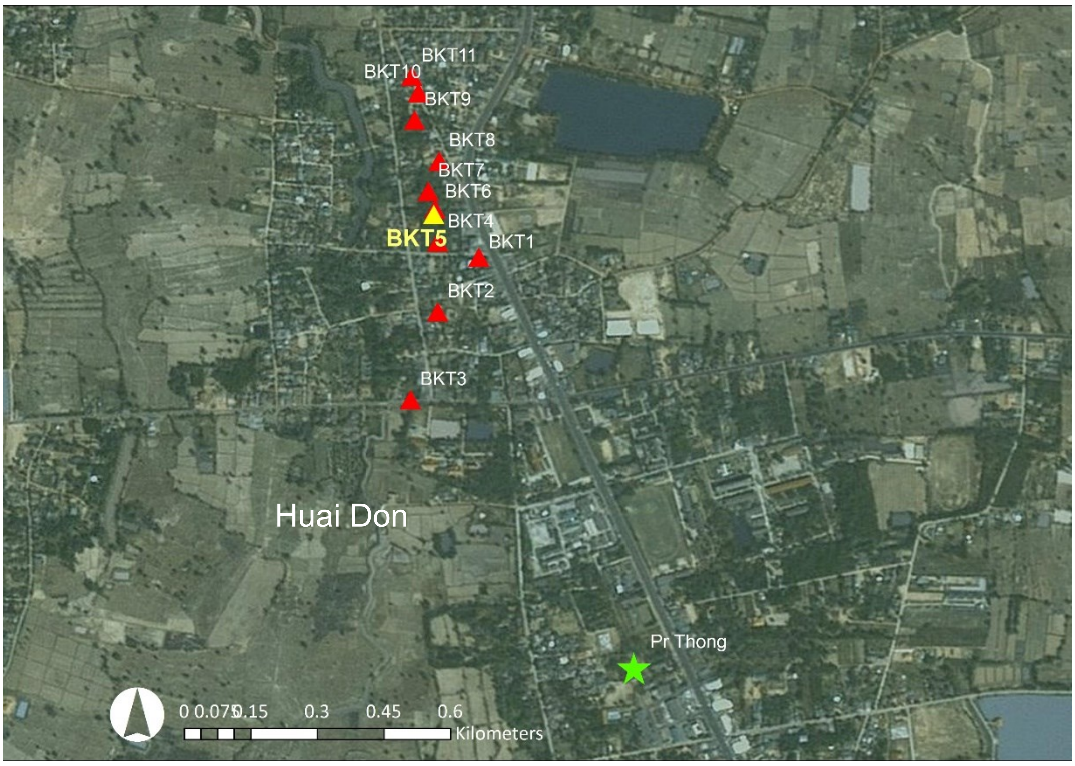


Figure 7.34 The distribution of slag deposits within Ban Kruat cluster. Prasat Thong is located to the south (green star). It should be noted that the author could access to only one site, marked in yellow colour (BKT5); other sites, marked in red colour, are assumed from the previous studies.

Due to the survey encountering difficulties, BKT5 was chosen since it was accessible (Figure 7.35). The site was a small low mound where only a small number of smelting slag fragments were found scattered. An interview with a landlady indicated that the site remained its original form, in recent times at least.

Figure 7.35 Small slag deposits in the property of Bang Phenduemphan (BKT4 and 5)

7.2.6 Ban Khok Rahoei/Border Police Patrol 221 headquarters (BPP)

Two small slag deposits were identified inside Border Police Patrol 221 headquarters. None of them retains their original shape (Figure 7.36). The first area was located in a corn field (BPP1), while the second area is under a building (BPP2). Although metallurgical remains were very sparse, it is noteworthy that local Khmer ceramic fragments, were found associated with slag, even though no Angkorian ceramic kilns were reported in this location (Prommanoj 1989; Lertlum *et al*. 2008, 22-23).

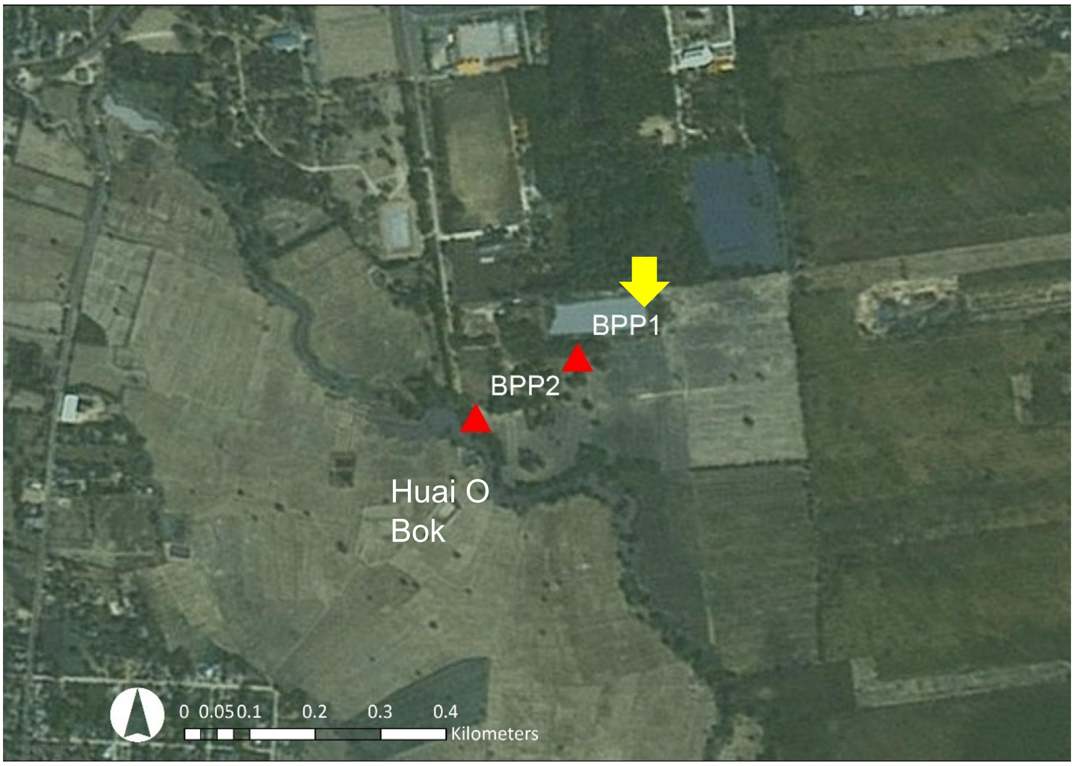


Figure 7.36 Two slag concentrations at the site of BPP221. The yellow arrow indicates the location where the laterite sample (BPPLAT) was collected.

Only a sample of geological laterite nodules was selected for the study in order to obtain information about locally geological laterite. It was found near a small reservoir which was dug into the underground laterite layer during the construction of reservoir, located north of BPP1, and dumped around its vicinity (Figure 7.37).

Figure 7.37 Images of a reservoir and a ground nearby covered by a laterite crust

7.2.7 Ban Sai Tho 8 South (STH8)

The cluster is arguably the largest and, fortunately, the most complete slag mound complex in Ban Kruat and morphologically distinct from other slag deposit clusters. Unlike the mounds in other clusters, which tend to be isolated, this cluster exhibits a ring of 11 slag mounds (Figure 7.38) surrounding a flat central area (Figure 7.39), thus creating a crater-like shape. This morphological difference makes this site exceptional as different activities could be expected at the two spatially distinct areas. This type of spatial arrangement had never been identified at other slag mounds or Iron Age settlement patterns in Northeast Thailand (e.g. Moore 1988; Nitta 1991; Suchitta 1983).

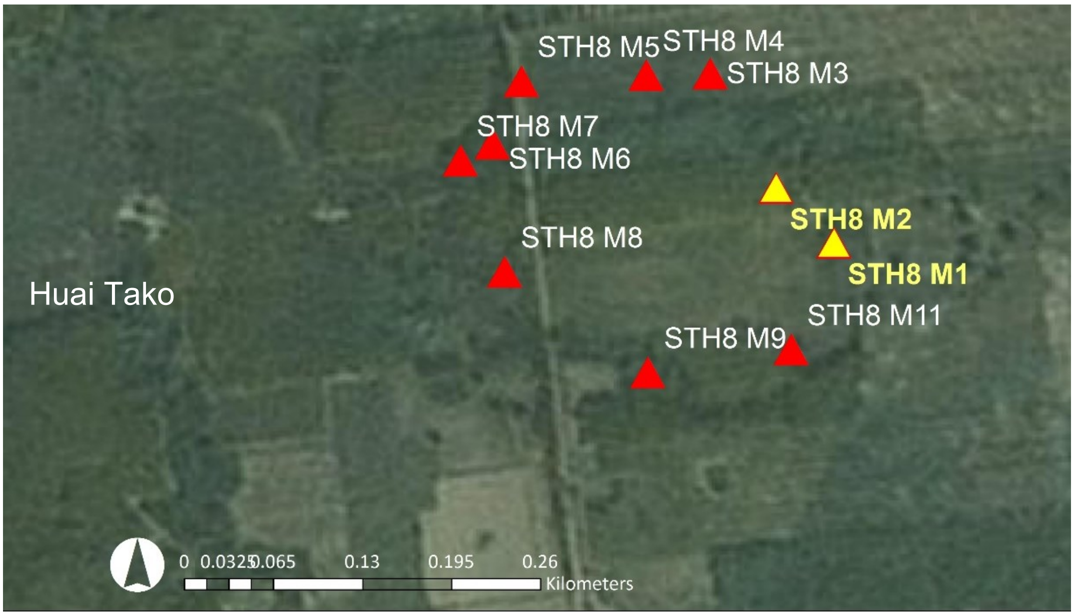


Figure 7.38 An aerial view of Ban Sai Tho 8 South cluster with Huai Tako on the left. The sites selected for analysis are marked by yellow symbols.

Figure 7.39 A view of central flat area looking toward Mound2 (left) and 1 (right) (red arrow).

The central flat area, is currently used for growing rubber trees and cassavas, while all slag mounds are undisturbed except the mounds STH8 M4 and M7 (Figure 7.40). This good preservation of most mounds allows a reliable impression of the original appearance of each mound. The height of the mounds ranges from 7-8m (STH8 M2-4, 9-11), 10-11m (STH8 M1) to 14-15m (STH8 M8) which makes them relatively larger than those in other clusters. Noticeably, this locale displays the largest mound concentration documented hitherto in Ban Kruat. Larger slag blocks were also found with half of them buried in the ground at the mound STH8 M3 (Figure 7.41). The author managed to expose one of it to see its internal structure. They are overall similar to Nong Chik; however, the slag blocks of this site had fragments of technical ceramics or baked clay attached or interwoven with slag.

Figure 7.40 Some mounds in Ban Sai Tho 8 South

(Top left: STH8 M1, top right: M3, and below: M8)

Figure 7.41 Two slag blocks found at STH8 M2. The one on the left in the top left image was moved from the earth and measured approximately 150cm long, 160cm wide, and 80cm high. The scale is 1.8m long (each block is 10cm wide).

7.2.7.1 The excavations at the central area (STH8 T1 and T2) and mound 2 (STH8 TP1)

Encouraged by the good preservation of this cluster, the LARP archaeology team conducted excavations for two seasons in 2009 and 2010. It should be noted that, the site was mistakenly coded as Ban Sai Tho7 for the excavation codename; even though, this cluster is located in the village of Ban Sai Tho8 (Lertlum *et al.* 2010, 167-209). In this thesis, the site is referred to STH8 Trench 1 (STH8 T1) and Trench 2 (STH8 T2) and STH8 Test pit 1 (STH8 TP1). The aims of the excavation were to explore if there was any functional difference between spaces identified, and whether it was possible to detect any other activities besides metallurgical processes. Two trenches at the flat/central area and one small pit at the mound STH8 M2 were designed to cover different areas (Lertlum *et al*. 2010, 167) (Figure 7.42).

The excavations successfully identified five different ancient occupational phases, three possible habitation and burial phases (Phase I-IV) and one metallurgical activity phase (Phase V) (Lertlum *et al*. 2010, 206). Since the results of the excavation have been fully reported (Lertlum *et al*. 2010, 167-209) and summarised in the previous chapter (see section 6.3.1), here only the metallurgical remains are discussed.

Figure 7.42 An aerial view showing locations of excavation pit and trenches

While the excavation at mound STH8 M2 produced very similar evidence to those found at Ban Khao Din Tai, the most remarkable finds came from the excavation at the central area. In STH8 T1, an interesting feature probably related to smithing activities was found (Figure 7.43). It was a layer which measured 3.2m by 3.6m and 30-35cm thick packed with the dense slag, which was mostly of plano-convex shape (Figure 7.45), in addition to ceramic sherds, glass beads, and laterite nodules (Figure 7.46). A probable hearth was also found at the southwest corner of this feature, made of low-fired clay and 72cm long, 54cm wide, and 14-15cm deep (Figure 7.44). This hearth appeared to have intentionally been set relatively higher than the surrounding slag floor. It was found in quite a good condition with only one part collapsed into the hearth. No lining, vitrification, or remains of slag or attached tuyère(s) were noticed inside the hearth. Nonetheless, as no tuyère port was identified on the well preserved hearth rim, it is assumed that, if present, any tuyère(s) could have been inserted from above and in a downward angle.

Considering the distribution of slag surrounding the hearth, slag could have been periodically cleaned, disposed to in the western area of the hearth, deposited, and, eventually, formed the hard floor of slag documented. Besides these features being potentially indicative of a smithing context (i.e. hearth and flat/convex shaped slag), the excavations failed to retrieve any hammerscale or iron droplets, though this might be attributable to lack of relevant training on the part of excavators or perhaps preservation issues. Some of the dense slag was therefore selected for further archaeometallurgical analysis, hoping to verify its connection to smithing and stage of this activity (primary and/or secondary). At STH8 T2, a similar type of slag was also found in large quantities in the upper layer, but no associated metallurgical installations – only few large blocks of baked clay.

In spite of the 2010 excavation in STH8 TP1, excavated slag was not available for analyses due to an accident that occurred during the recording session. Instead, the metallurgical remains from the mound STH8 M1 were chosen since they were broadly comparable in their appearance and context of origin. Samples from the suspected smithing feature (i.e. dense slag and laterite nodules) were included. A laterite sample from a geological context found near the mound STH8 M6 and a clay sample from a nearby stream were also subjected to analysis.

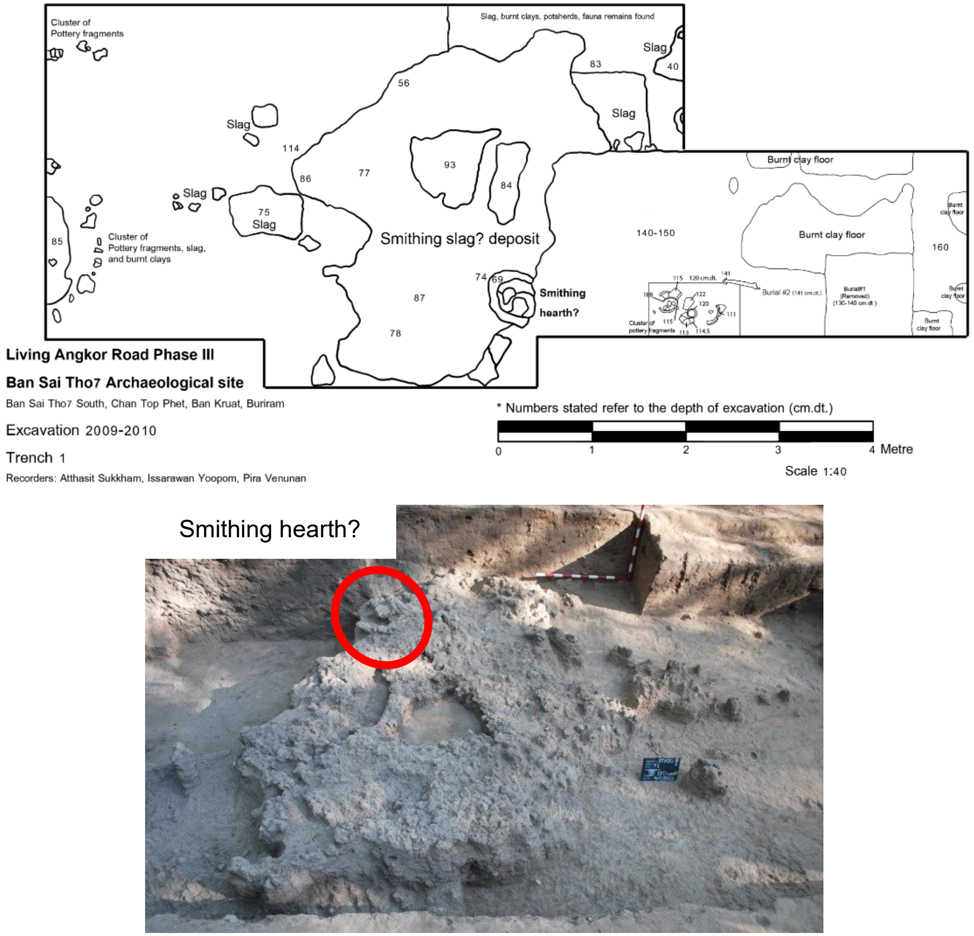


Figure 7.43 Excavation plan (top) and photo (below) showing a feature which is thought to have been a smithing workshop

(Top image: courtesy of the Living Angkor Road Project)

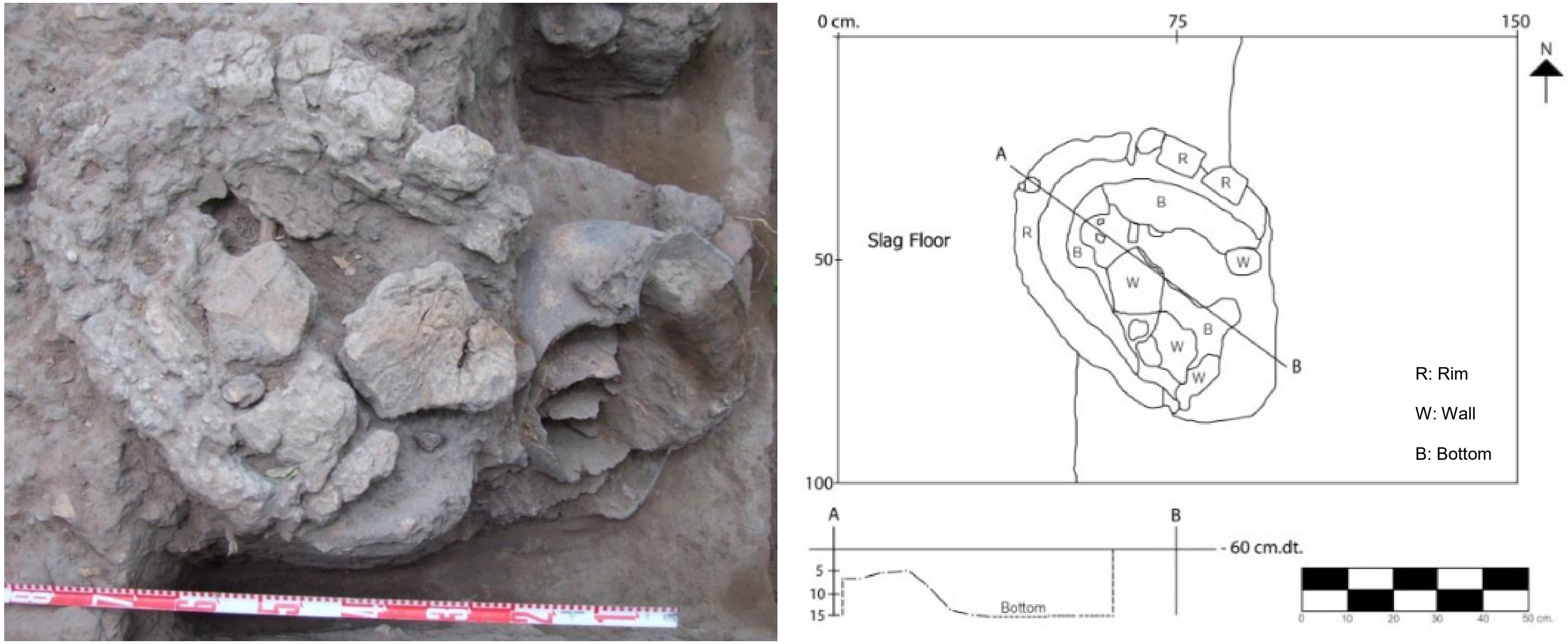


Figure 7.44 Probable smithing hearth. It was presumably built on the working floor and, subsequently, shaping clay into an oval shape with a thick rim.

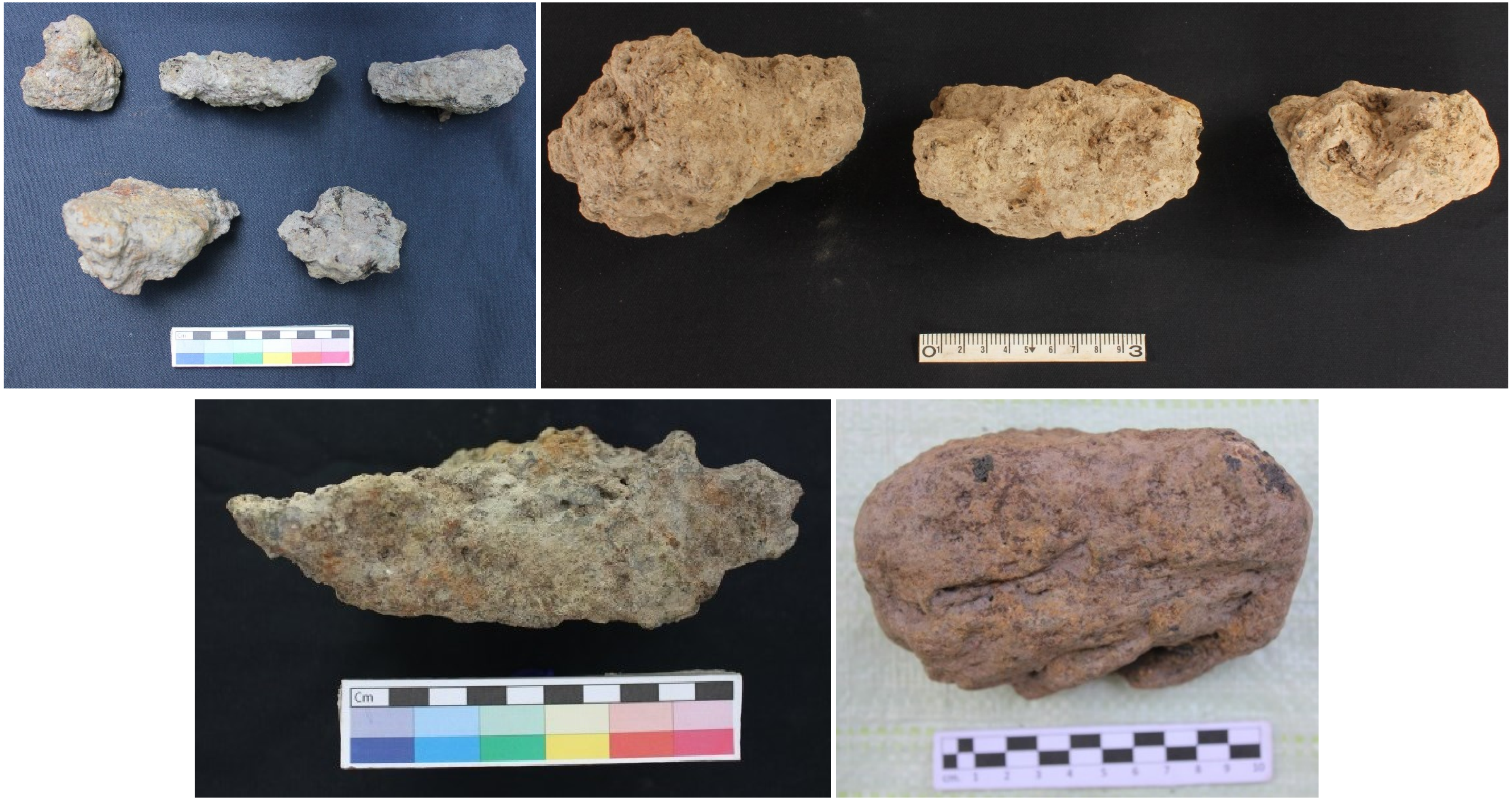


Figure 7.45 Examples of flat/convex and irregular-shaped slag (lateral view)

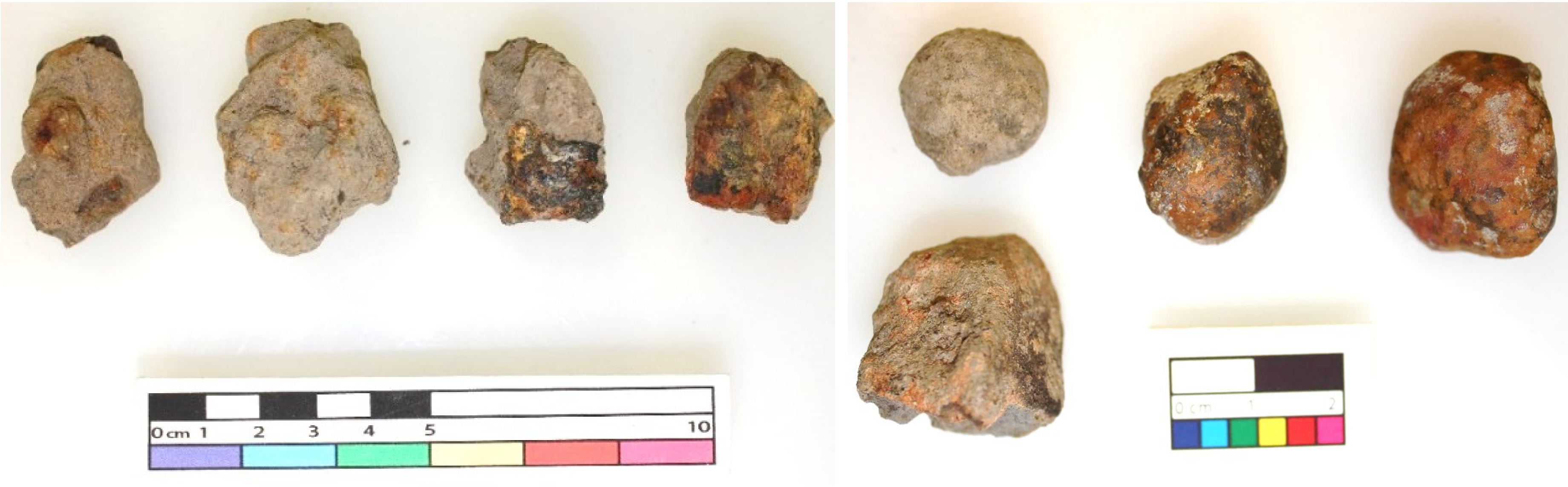


Figure 7.46 Examples of laterite nodules/pisoliths

7.2.8 Ban Sai Tho 8 South 2 (STH8/2)

Here is another large group of slag deposits consisting of six mounds in a fair condition located approximately 500m south of STH8 (Figure 7.47 and 7.48). All mounds except the mound 6 were disturbed by the preparation of the land. Joining slag mounds between STH8/2 M1 and M2 (Figure 7.49) and slag block, similar to those found at STH8 M3 (STH8/2 M4) were also documented in this area (Figure 7.51).

Mound STH8/2 M6, the only undisturbed deposit, was selected for sampling (Figure 7.50). This was a small mound, approximately 15m in diameter and 1.5-2m high, with slag and few technical ceramics visible on the surface.

Figure 7.47 The location of Ban Sai Tho 8/2. The site selected for analysis is marked by the yellow symbol.

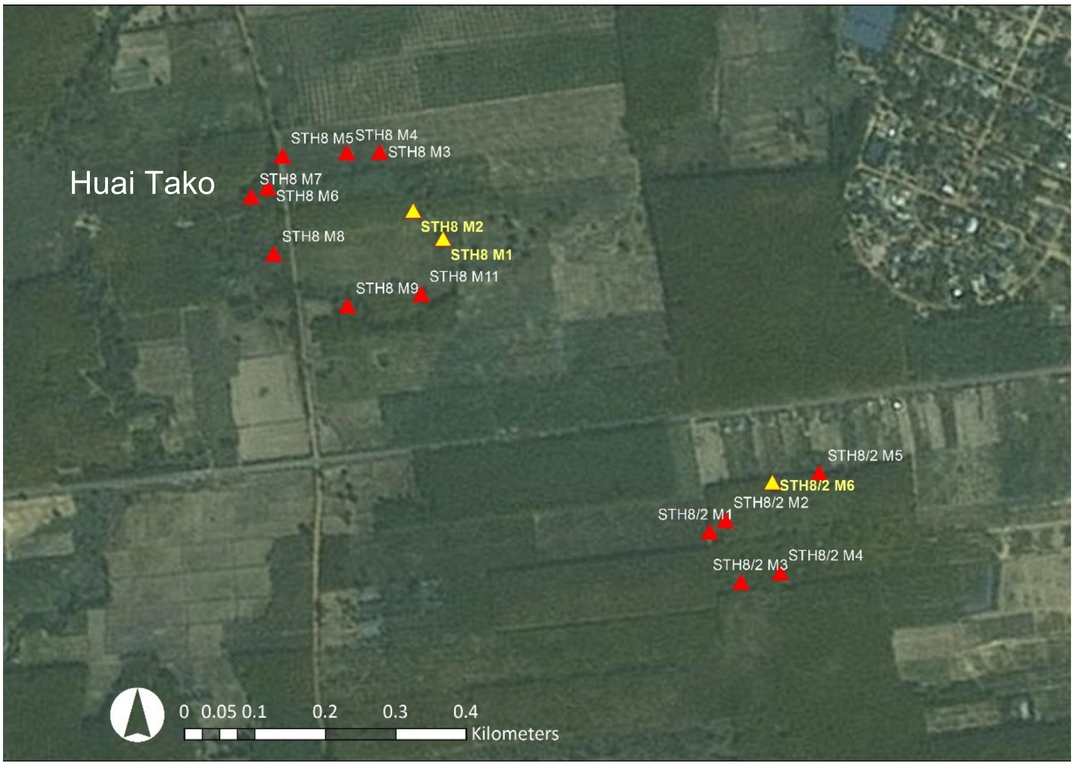


Figure 7.48 The locations of Ban Sai Tho8 and Ban Sai Tho8/2

Figure 7.49 Two joining slag mounds (STH8/2 M1 and M2)

Figure 7.50 The mound STH8/2 M6 chosen for analysis

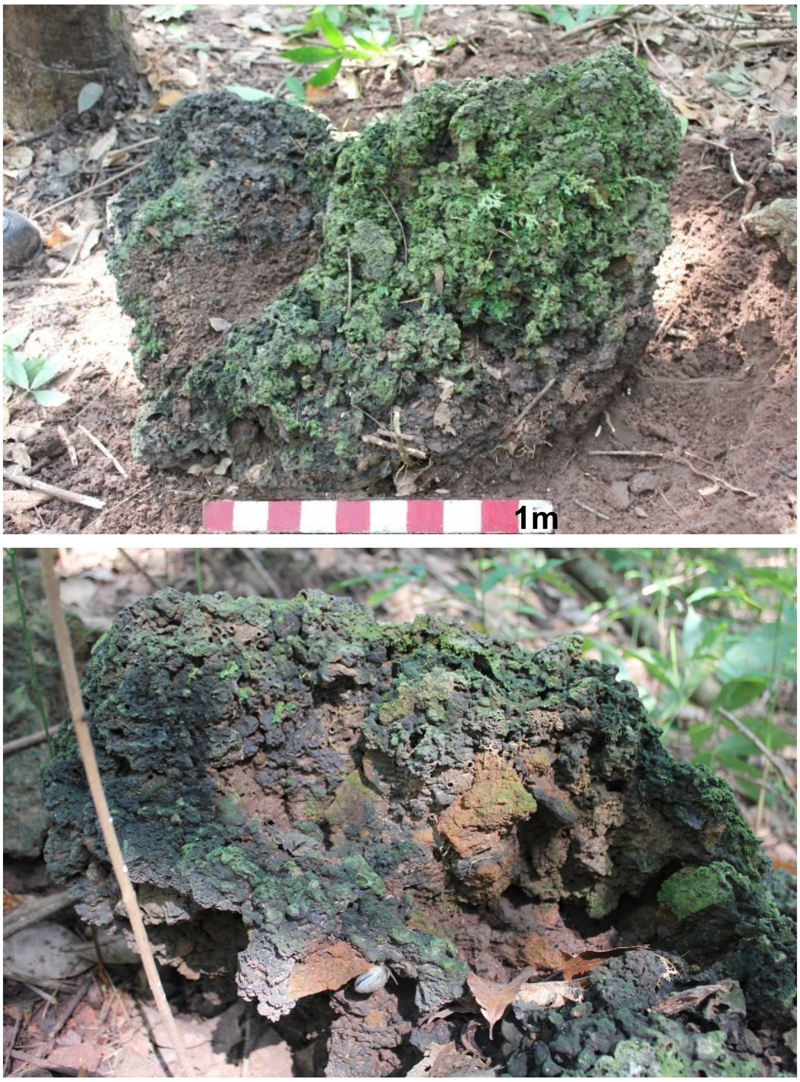


Figure 7.51 The large slag block found at the mound STH8/2 M4. The size is approximately 150cm long, 110cm wide, and 130cm high with part of it below ground surface. Baked clay or probable technical ceramics are clearly seen in between slag.

7.2.9 Ban Sai Tho 10 North (STH10)

This is the easternmost smelting site recorded in Ban Kruat (Figure 7.52 and 7.52). According to the landowner, there used to be large mounds on this location before the 1960's, but only relatively small clusters of metallurgical waste could be documented during the survey. Judging by the highest concentrations of the remains at STH10 B and S, they might have been the original locations of slag mounds.

Samples selected as representative for this cluster were from the southern area (STH10 S) where slag and both complete and fragmentary technical ceramics (i.e. clay plugs) appeared on the surface (Figure 7.54).

Figure 7.52 The distribution of the slag concentrations in STH10; Huai Tako is on the right side of the site. A studied site is represented by the yellow symbol.

Figure 7.53 The site of STH10 as looked from the south. The terrain where metallurgical remains appear is relatively higher than surrounded areas

Figure 7.54 The south area (STH10 S), marked by dotted red line, one of two highest concentrations of metallurgical remains, where the samples of slag and technical ceramics were collected. A complete clay plug was also recovered.

7.3 Initial discussions and observations on the sites and their remains

7.3.1 Proposed chronological framework for Ban Kruat iron production

The dates of the sites and their archaeological features are fundamental, as a backbone for the contextualised technological study that this research aims to provide. In Thai archaeology, most slag deposits are often dated to “ancient periods”, which is quite common in documenting metallurgical sites without datable finds associated. For Ban Kruat area, the partial nature of archaeological studies has resulted in an incomplete chronology. As discussed in Chapter 6, archaeological evidence appeared to document only two discontinuous phases: the Iron Age (500BC-AD500/600) and the Angkorian period (11^{th}-13^{th} century AD). For the remains of iron production recovered prior to 2007, they had never been clearly dated, but they were speculatively associated with the Angkorian ceramic production, and hence assumed to date to the same period (Chaikulchit 1997, 15).

When LARP excavated two slag mounds, two absolute dating techniques were applied in concert with a traditional relative dating determination, in order to elucidate how long the production lasted (Lertlum *et al.* 2008, 112; Won-In 2011) (see Appendix E for detail discussion on each prior attempt). The radiometric dating was firstly employed (Lertlum *et al*. 2008), but the calibrated result was unable to scope the possible period when the operation might be carried out. The second attempt employed thermoluminescence technique (TL); the result again raised a concern over the reliability of the dates provided due to the differences in the quantification of potassium (K), which is one of the important sources to measure dose rate (Duller 2008).

As the previous attempts remain questionable and the need of this thesis to ascertain the chronology of the production in order to frame the direction of this thesis’s interpretation, the author sent the charcoal samples from KDT2 and STH8 T1 to be dated by accelerator mass spectrometric (AMS) dating. The result was then compared with the ceramic chronology in order to assess the reliability of the dates obtained. The final suggested dates are applied to this thesis.

7.3.1.1 AMS dating

Upon realising the problem with the TL dating determination, the author finally resorted to AMS dating technique serviced by Beta Analytic Laboratory based in United States. This technique permits radiometric dating of very small samples, hence allosing to determine dates for small charcoal specimens embedded in the slag. Financial support was obtained from the UCL Institute of Archaeology and the UCL Graduate School to submit five samples to the laboratory. Within these financial and logistical constraints, samples from excavated archaeological records were chosen. Three samples were selected with the aim of covering the full chronological span for the site of Ban Khao Din Tai. One of these, KDT170cmdt, was specifically selected from the same context as other samples previously dated by other techniques. The second and third samples (KDT247cmdt and KDT368cmdt) were collected from deeper excavation level. For Ban Sai Tho7, the two samples were recovered, respectively, from a smithing context and from a burial, which had been thought to represent a pre-metallurgical activity.

The calibrated dates from AMS are conspicuously different from those obtained previously; the only similarity was found with the TL dates in terms of the low variability, but absolute values were significantly different. The results range from calAD 222 to calAD 539 and thus consistently dated their respective contexts to the late Iron Age (3rd-6th century AD) (Table 7.1 and 7.2, Figure 7.55) after calibrated with Oxcal 4.2 (Ramsey 2013) and IntCal 13 (Reimer *et al.* 2013). It should be aware of that the species of these charcoal samples have yet been identified; therefore, a problem of "old wood" problem may affect the determination.

In sum, the most recent attempt to date the excavated slag mounds using AMS dating yielded five clustered dates, all falling in the Iron Age, which defied expectations but had no reason to be questioned. Overall, considering the complications with scientific dating over the course of the programme, the AMS dates are deemed the most reliable, but these results are considered together with the relative dates suggested by associated archaeological artefacts in order to obtain a more comprehensive picture.

Lab no.	Sample	Context	Date (BP)	Calibrated date range (AD) (95.4% probability)	Calibrated date range (BP) (95.4% probability)
Beta-386737	KDT170cmdt	KDT'08 #088 NWQ EXT, 170 cm.dt. (in slag)	1700±30	253-304 (23.6%) 313-406 (71.8%)	1697-1647 (23.6%) 1637-1544 (71.8%)
Beta-386738	KDT247cmdt	KDT'08 #046 SWQ, 247 cm.dt. (in slag)	1690±30	256-299 (16.3%) 318-416 (79.1%)	1694-1651 (16.3%) 1633-1534 (79.1%)
Beta-386739	KDT368cmdt	KDT'08 #136 SEQ, 368 cm.dt. (in slag)	1750±30	222-385	1729-1565

Table 7.1 AMS results of the charcoal samples collected at KDT 2. Calibration was done with Oxcal 4.2.3 (Ramsey 2013) using curve IntCal13 (Reimer *et al.* 2013).

Lab no.	Sample	Context	Date (BP)	Calibrated date range (AD) (95.4% probability)	Calibrated date range (BP) (95.4% probability)
Beta-386740	STH88cmdt	STH7'10 #049 T.1 N1 88 cm.dt. (charcoal collected from the smithing context)	1620±30	382-539	1569-1412
Beta-386741	STH116cmdt	STH7'09 #137 T.1 EQ B#1 (charcoal collected beneath the skull of the burial #1)	1700±30	253-304 (23.6%) 313-406 (71.8%)	1697-1647 (23.6%) 1637-1544 (71.8%)

Table 7.2 AMS results of the charcoal samples collected at STH8 Trench I. Calibration was done with Oxcal 4.2.3 (Ramsey 2013) using curve IntCal13 (Reimer *et al.* 2013).

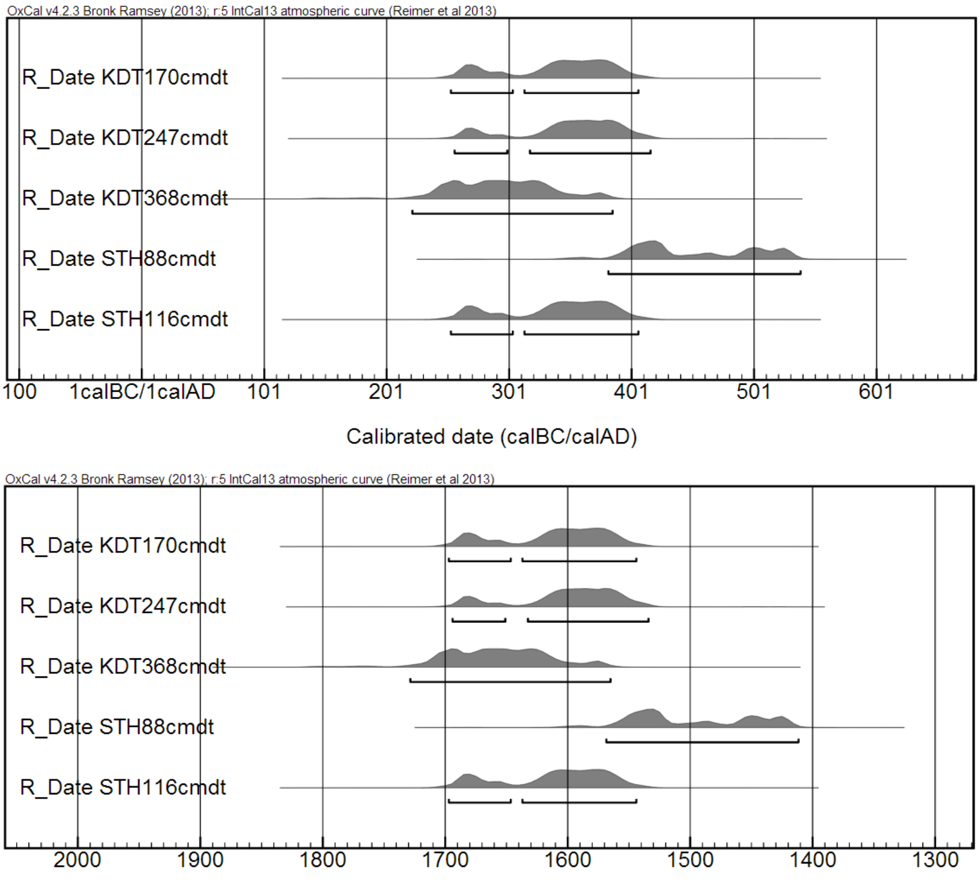


Figure 7.55 Probability distributions of calibrated radiocarbon dates of KDT 2 and STH8 Trench I (calBC/calAD (above) and calBP (below))

7.3.1.2 A comparison between AMS result and ceramic chronology

Apart from the absolute dating techniques, ceramics are informative in allowing to assign contexts to phases of the Thai chronology based on comparisons with the dated ceramics found in Lower Northeast Thailand and its vicinity (i.e. Brown 1983; Higham *et al.* 2007; Higham and Kijngam 2009, 2010, 2011, 2012; Thammapreechakorn 2009; Welch and McNeil 1988-1989).

The excavations at two slag mounds yielded very similar collections of different types of ceramics, mostly as fragments of earthenware. Of these, reduced utilitarian wares dominated (Figure 7.56 and 7.56) which typologically match the Iron Age Phimai black pottery that has been dated to 200 BC–AD650 (Higham 2011b, 117, 128; Higham *et al.* 2007, Chapter VII; McNeil 1997, 172; McNeil and Welch 1991; Welch and McNeil 1988-1989) (Figure 3.9) (see section 3.3.2 and 6.3.1). Noticeably, however, this Phimai black pottery has also been found in association with Khmer ceramics in the Angkorian Khmer settlements surrounding Phnom Rung and Muang Tam Khmer complexes (Jumprom

2005). At Phimai, Phimai black pottery was found underneath the building foundation (Talbot and Janthed 2001 188-189; Welch 1989, 20), so this pottery may have been continuously used in the transition period (see section 3.3.3) or probably Angkorian period (see section 3.3.4) but not as a dominant pottery type. On a wider geographical scale, this reduced ware group was shared among the communities stretching from lower Northeast Thailand to the Mekong Delta in Cambodia (Fehrenbach 2009, 2010). It was also found at the late Iron Age site of Phum Snay (Akayama 2013; Miyatsuka and Yasuda 2013) (Figure 7.58) and at the looted site at the Souphi Village in Banteay Meanchey, Cambodia. The temporal span for this type broadly falls in the Iron Age of mainland Southeast Asia (500BC-AD500) (Fehrenbach 2010). Overall, thus, the bulk of the pottery excavated pointed to Iron Age dates, in agreement with the AMS determinations.

Figure 7.56 Examples of reduced ware group found at KDT2 (above) and in STH8 T1 (below)

Figure 7.57 Examples of reduced bowls and bowls with pedestal found at Ban Bueng Noi

Figure 7.58 Examples of reduced ware from the Iron Age site of Phum Snay in Cambodia

(Images: Fehrenbach 2010, 15)

The presence of agate beads at Ban Sai Tho7 (Lertlum *et al*. 2010, 198) further constrained the date of the sites to the Iron Age, or possibly the early historical periods (c. 500AD). This ornament appeared as a result of the intensified maritime trade with India during these periods (Bellina and Glover 2004; Carter 2013).

AMS dates and the reduced wares thus support the idea that the sites were in operation during the later Iron Age, but there is further ceramic evidence worth mentioning that indicates further activity during the succeeding phases. In upper excavation levels of KDT2, a few 11^{th}-13^{th} century AD local Khmer ceramic fragments and one piece of Ming dynasty Chinese stoneware were also retrieved from (Figure 7.59). Furthermore, one Khmer stoneware was recovered from STH8 TP1, implying occupations or probable metallurgical activities after the Iron Age. Unfortunately, the author lacks direct dates for the other slag deposits surveyed. In a few mounds (NC4, KDT7, BPP1, and STH8 M11), however, Khmer ceramics were found on the surface. Furthermore, some mounds within Khok Yang and Nong Chik sit beside Angkorian ceramic mounds. If we recall the possibility of the continuation of the use of Phimai Black pottery, altogether the evidence allows the proposition that the metallurgical activities continued into the later cultural phases, possibly into the Angkorian period. This could concur with the rich Angkorian evidence recovered in the broader area which might point to links between the metallurgical sites and the settlement patterns typical of the Angkorian period. Evidence from lower Northeast Thailand has shown that many prehistoric settlements underwent a cultural and political assimilation into Angkor, especially those with valuable resources, such as fertile lands, metals, salt, and stone. Most likely, Ban Kruat was not an exception to this, and it is thus plausible that occupation and metallurgical exploitation continued from the Iron Age to the Angkorian period. The ongoing project (Iron and Angkor) which seeks to find through slag inclusion analyses the iron made in Ban Kruat in Angkorian temples and constructions elsewhere (Stéphanie Leroy and Mitch Hendrickson pers comm. 11th December 2014). If the result is positive for Ban Kruat, this would be indirect evidence for the continuation of Ban Kruat iron exploitation into the Angkorian period.

It remains puzzling that none of the few AMS dates obtained fall in the later periods, but this might be explained by the limited number of samples and excavated contexts.

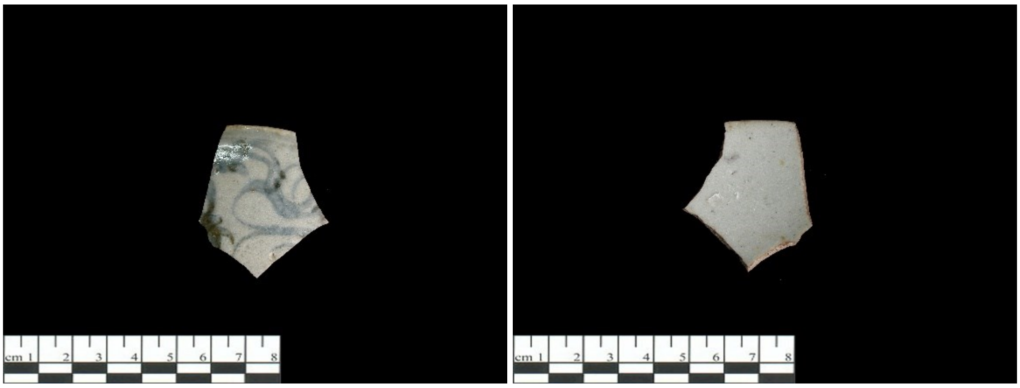


Figure 7.59 A piece of Chinese Ming-Dynasty stoneware

7.3.1.3 The proposed dates for the excavated sites and revised chronological frameworks

Despite our best efforts, the chronology of metallurgical activities at Ban Kruat remains somewhat uncertain. A critical assessment and integration of scientific dating and a comparison with ceramic chronology allow a preliminary proposal, which will no doubt be refined and completed in future work.

The latest and most reliable scientific dating determinations place the excavated sites in the late Iron Age (3^{rd}-6^{th} century AD) which coincides with the predominantly Iron Age and, probably, early historic archaeological indicators found at both sites. Accordingly, the proposal that the main activities fall in the Iron Age seems indisputable. Based on additional archaeological evidence for later periods, however, it is proposed that the operation might have continued by the successors of the Iron Age inhabitants. The landscape of Ban Kruat, dominated by Angkorian Khmer remains, lends support to this claim. It would seem that a resource-hungry expanding Empire would have overlooked an established tradition of ironmaking at Ban Kruat. All in all, the chronological framework adopted in thesis assumes that Ban Kruat would have been settled in the Iron Age, and that iron production started in this period. Metallurgical activities could have been developed and further consolidated in the Angkorian period, together with other industries such as ceramic and stone.

The limitations of this chronological model are explicitly acknowledged. In particular, as we lack specific dates for the lifespan of individual production locales, it is virtually impossible at this stage to reconstruct the evolution of the production landscape over time, or to systematically assess fluctuations in production scale or technological developments. However, it is still possible to attempt a detail technological characterisation of the metallurgical tradition materialised at Ban Kruat, which may serve as a basis for future comparisons and diachronic assessments.

7.3.2 Some thoughts on the metallurgical remains: a preliminary visual comparison

Before the technical data (macro- and microstructural and chemical) are brought into the picture, it is appropriate to summarise the information recovered during the fieldwork and the macroscopic assessment of the remains. This information will complement the laboratory analysis and help refine the hypotheses and research questions, to be addressed in following chapters.

The following sections present findings that were obtained from the investigation of all slag deposits (47 sites) and subsequent detailed macroscopic examination of some slag deposits (24 sites), including the excavated collection of KDT2 and STH8. In total, 704 slag samples, 60 samples of technical ceramics, and 15 potential ore samples were included for macroscopic evaluation (see Appendix D for a summary of samples collected and examined). Each group is discussed separately below. Here their appearances and some notable features are preliminarily described and commented, whereas the results of detailed structural (macro and micro) and chemical analyses will be discussed along with interpretations in the next chapter.

7.3.2.1 The slag

During the survey, slag was found to dominate the surface of all slag deposits. A visual comparison of slag samples suggests that they can be macrostructurally divided into three main groups. The first and by far the most abundant is represented by amorphous and bulky slag of various sizes (ranging from 6cm to 15cm length, 6cm to 13cm width, and 4cm to 9cm in thickness) and weight (ranging 91g to 1160g) (see Appendix F for a summary of slag collected). Although a macroscopic comparison of slag samples from different slag sites shows that their appearance is largely comparable (Figure 7.60-7.73 and Appendix C), the size and weight data show a level of variation, particularly the weight that varies significantly (Figure 7.76). However, the data also suggest that slag deposits may be largely divided into two groups (Figure 7.77) where the slag samples in the first group, consisting of the clusters located on the eastern part of the surveyed area, is comparatively smaller and lighter than the second (western) group, associated with Ban Sai Tho group (STH8, STH8/2, and STH10) (Figure 7.74 and 7.75).

Most of them exhibit a relatively smooth surface, suggesting a contact with ground or furnace wall or lining, whereas the other side shows rough surface with porosities, implying much gas generated during the smelting. It is noticeable that very few of the samples, mostly in small sizes, show a flow, lava-like texture that is characteristic of slag that flowed out of the furnace whilst molten (Figure 7.67). According to their small sizes, they may have been created within and removed from furnace rather than intentionally tapped. This clearly challenges the previous suggestions that the slag was tapped or drained to a cooler zone (Chuenpee *et al.* 2014, 942; Venunan 2011, 73; Yoopom 2010, 115).

When crushed, slag lumps in this first group can ostensibly be classified according to their porosities: porous, semi-porous, and dense, as observed in a previous study focused on a single site (Venunan 2011) (Figure 7.78). As per the previous suggestion, all of these can be categorised as furnace smelting slag (Chuenpee *et al.* 2014; Venunan 2011). Of three slag types classified (419 samples examined), semi-porous slag forms the majority of the collection examined at each site (making up more than 50% of each collection) followed by porous and dense slag. However, semi-porous slag can also be structurally diverse for some can be denser or more porous than others in the same group. Please also note that this observation is based on 15 slag deposits that had at least 15 samples collected (see Appendix G for a result summary). This grouping is also evident when they are examined by their density. As expected, the porous slag group has the lowest density followed by semi-porous and dense group respectively (Table 7.3). The density of slag samples in the semi-porous group varied more than others. Their differences in density are possibly influenced by porosity, iron particles trapped, and, probably, the contents of iron oxides remaining in slag (i.e. the more iron oxides slag contains, the heavier slag can be).

These findings will be evaluated together with the technical data to assess the extent to which they suggest a technical variation within similar practices or different smelting traditions. Slag samples for further laboratory analyses were selected from different slag sites for this evaluation. The samples selected are indicated by red boxes shown in the images of slag below and in Appendix C (Figure 7.60-7.73).

Figure 7.60 Slag samples collected from the surface of KY4 (ventral view).

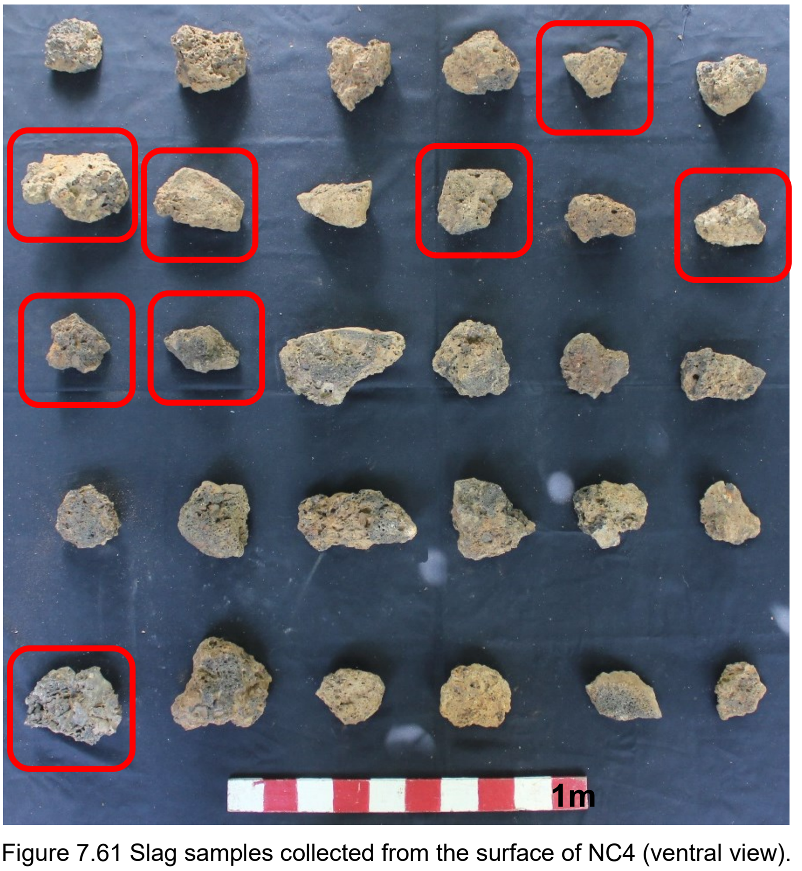


Figure 7.61 Slag samples collected from the surface of NC4 (ventral view).

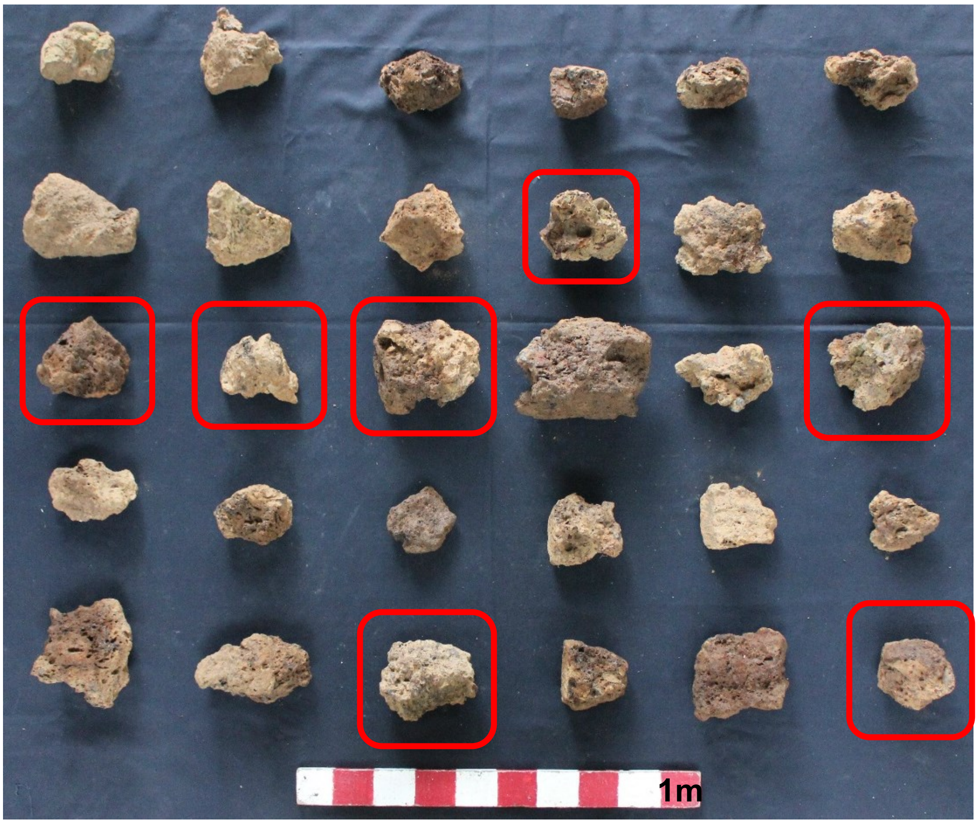


Figure 7.62 Slag samples collected from the surface of KSK1 (ventral view)

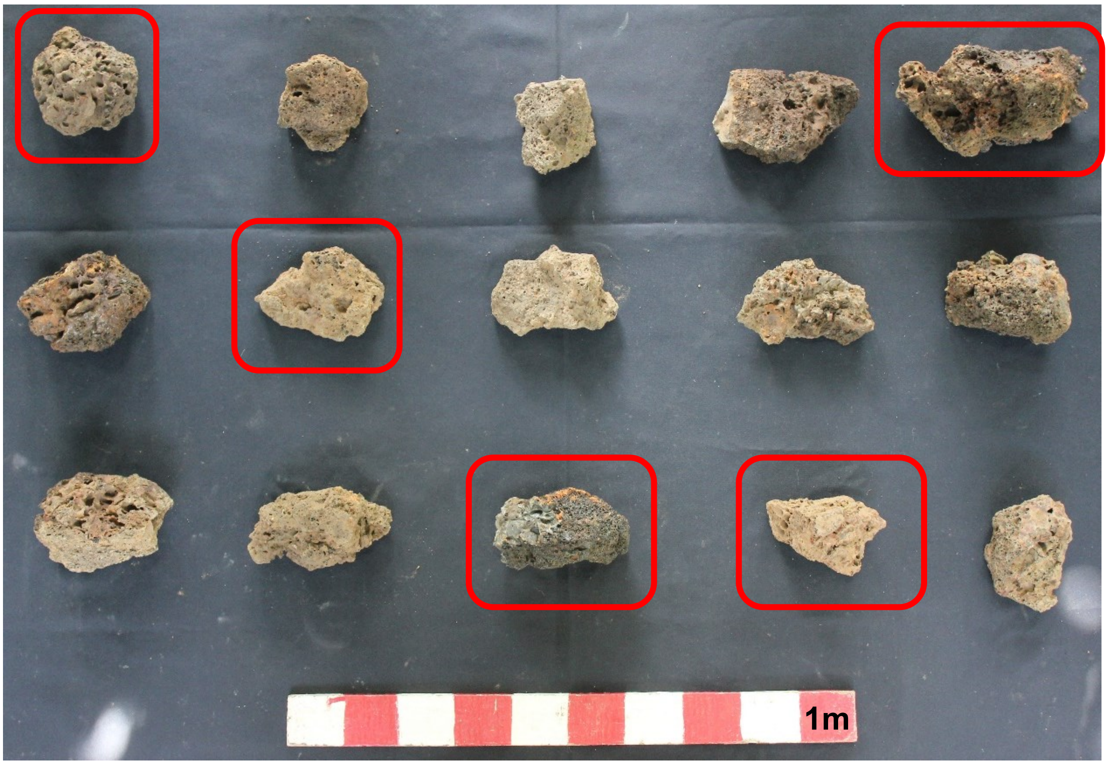


Figure 7.63 Slag samples collected from the surface of KDT1 (ventral view)

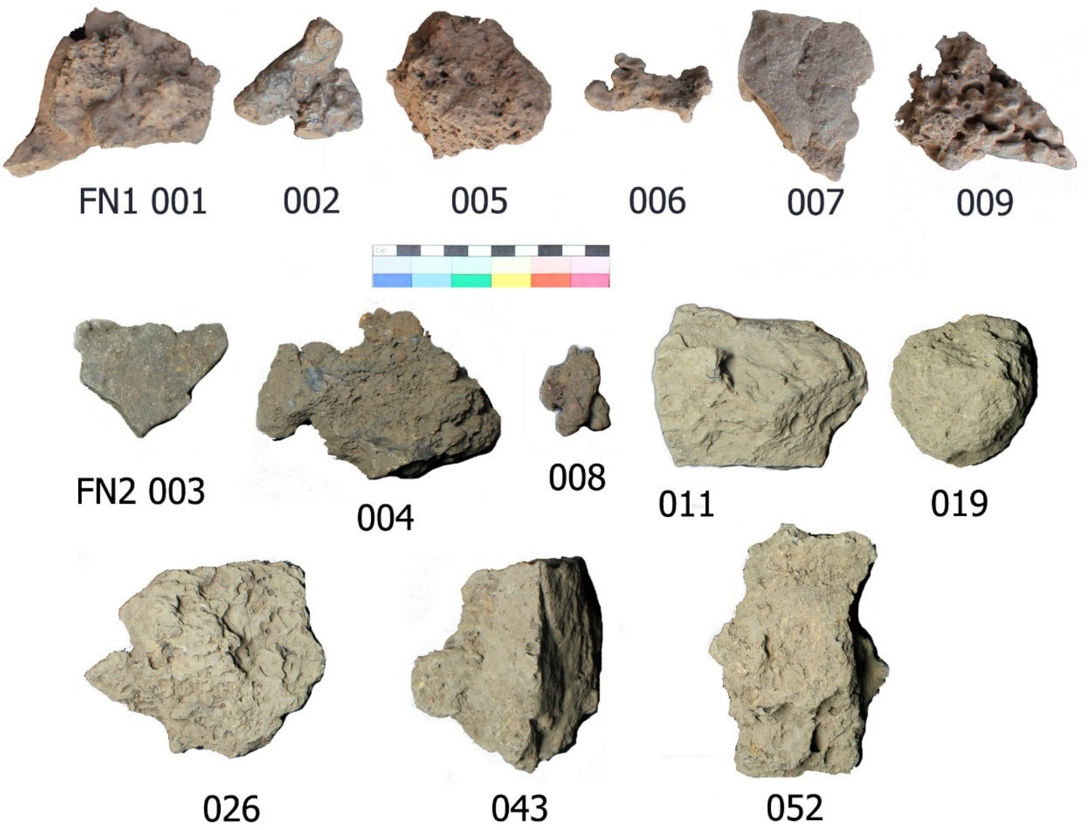


Figure 7.64 Slag samples collected from the furnace 1 and 2 (excavation level 3-5) at KDT2 for further analyses (ventral view)

Figure 7.65 Examples of slag excavated at KDT2 excavation level 5 (ventral view)

Figure 7.66 Examples of slag excavated at KDT2 excavation level 6 (ventral view)

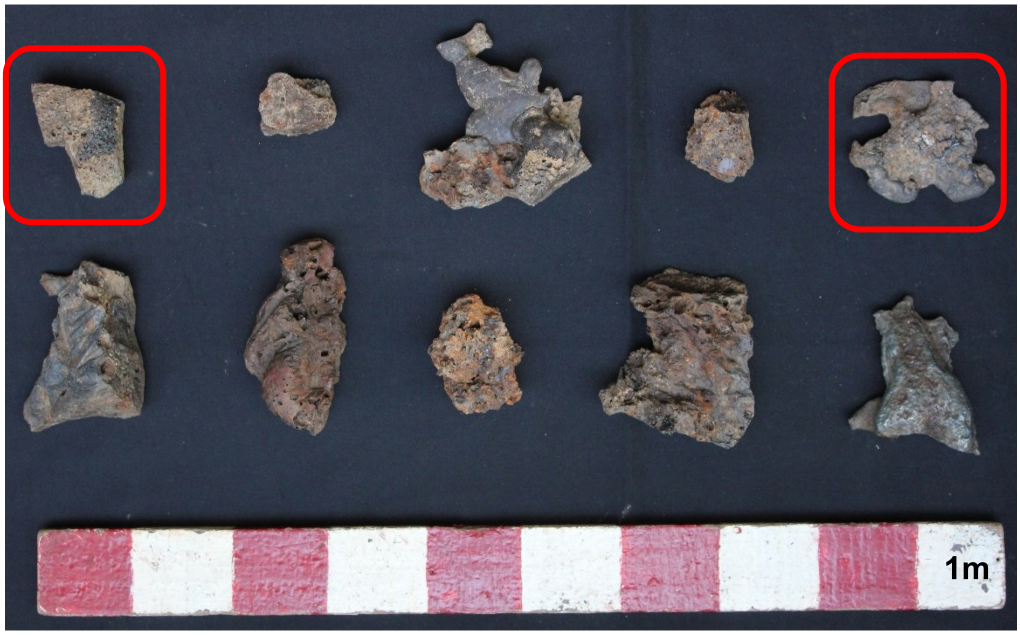


Figure 7.67 Examples of slag excavated at KDT2 excavation level 10 (ventral view)

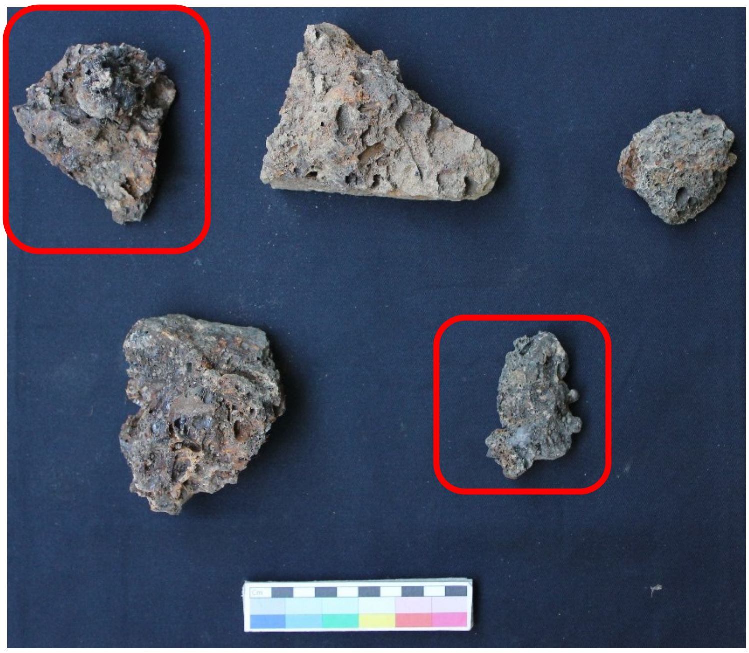


Figure 7.68 Examples of slag excavated at KDT2 excavation level 18 (ventral view)

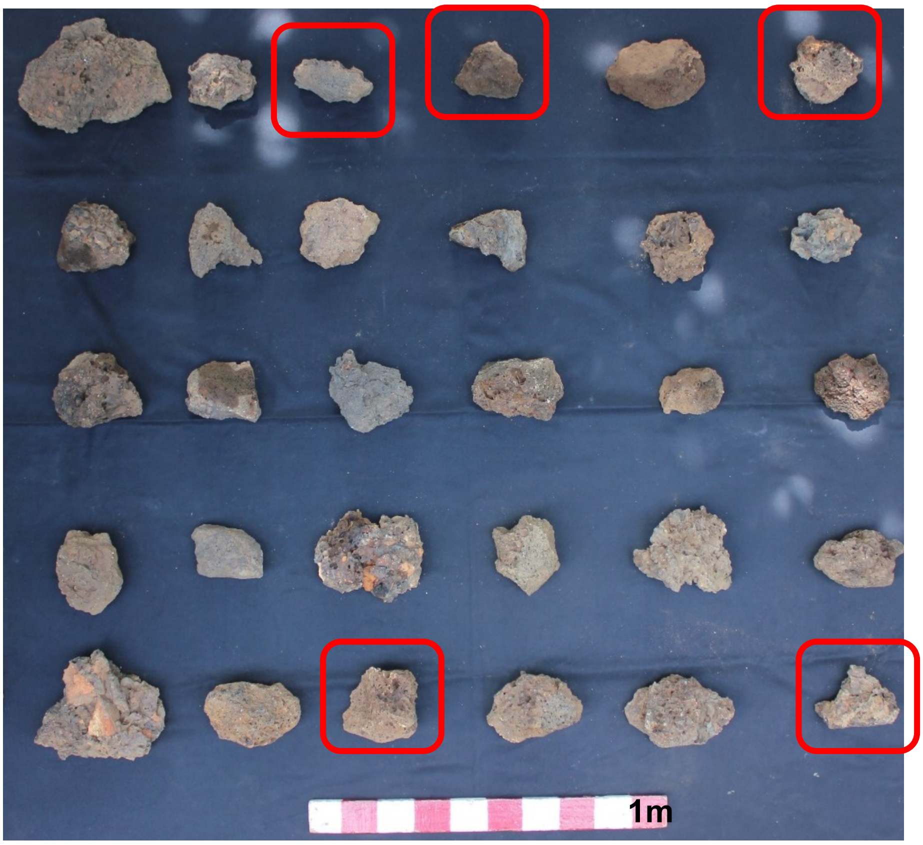


Figure 7.69 Slag samples collected from the surface of KDT3 (ventral view)

Figure 7.70 Slag samples collected from the surface of BKT5 (ventral view)

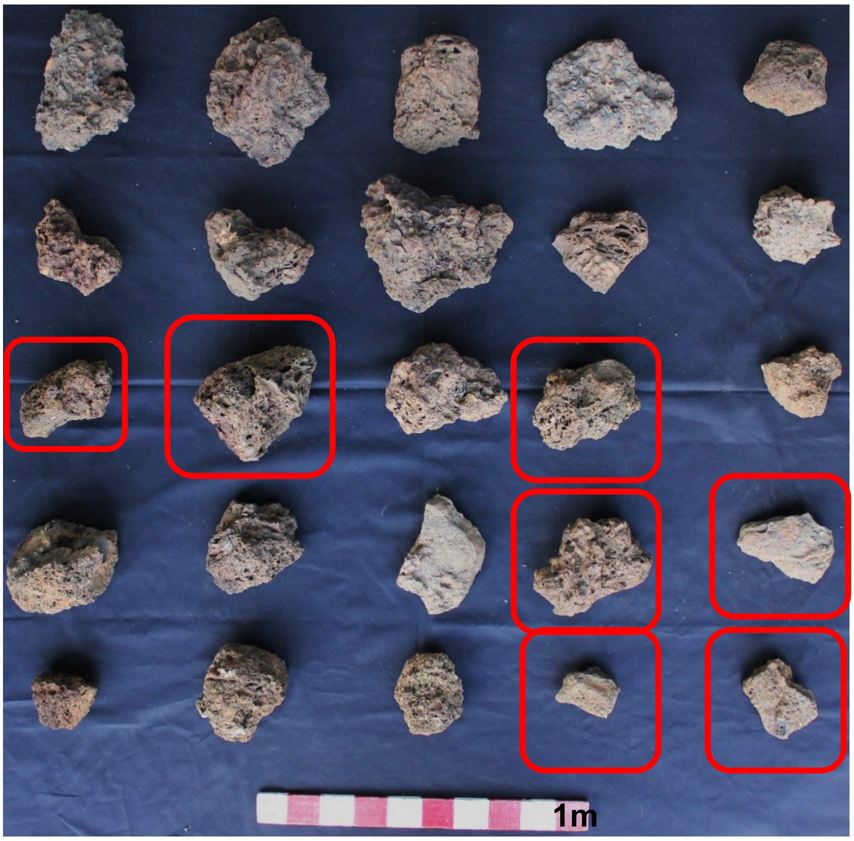


Figure 7.71 Slag samples collected from the surface of STH8 M1 (ventral view)

Figure 7.72 Slag samples collected from the surface of STH8/2 M6 (ventral view)

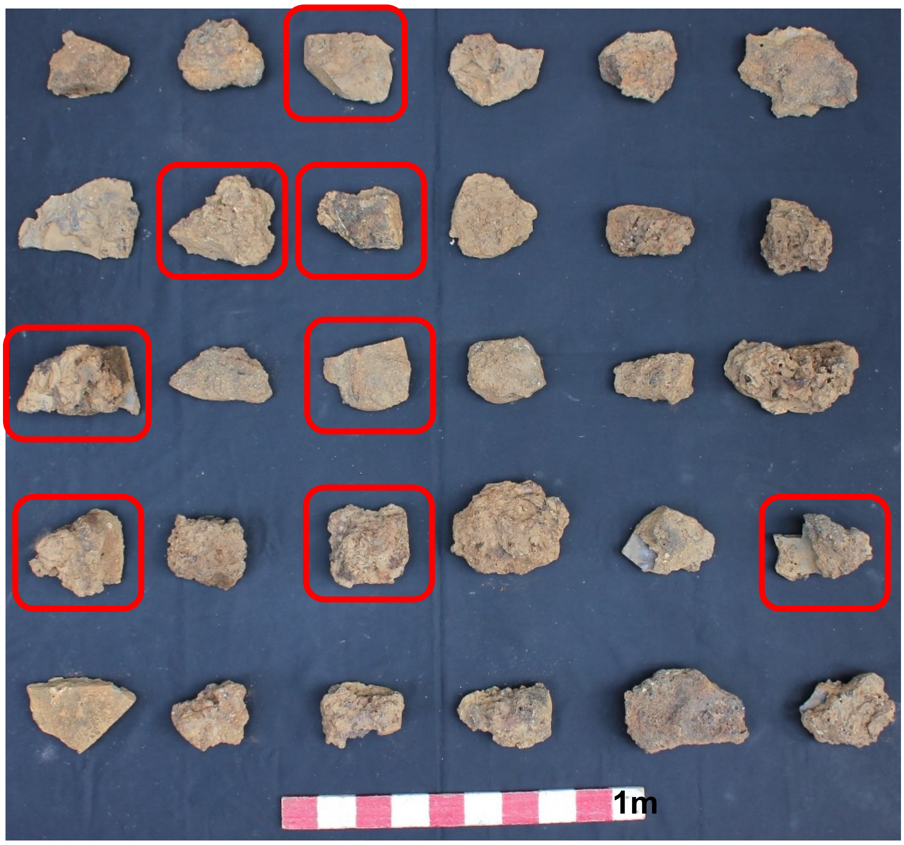


Figure 7.73 Slag samples collected from the surface of STH10 S (ventral view)

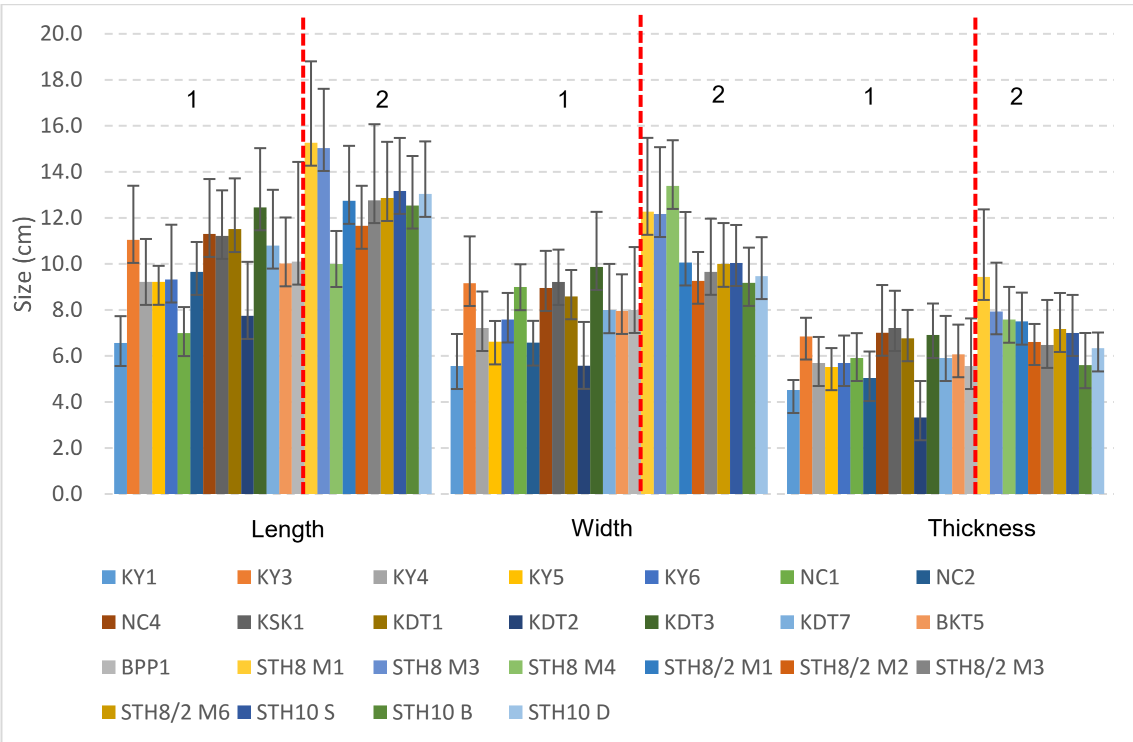


Figure 7.74 Bar chart shows average sizes of slag samples from 25 slag deposits. The error bars show the standard deviations. Two slag deposit groups (1 and 2) are suggested, indicated by the dotted lines.

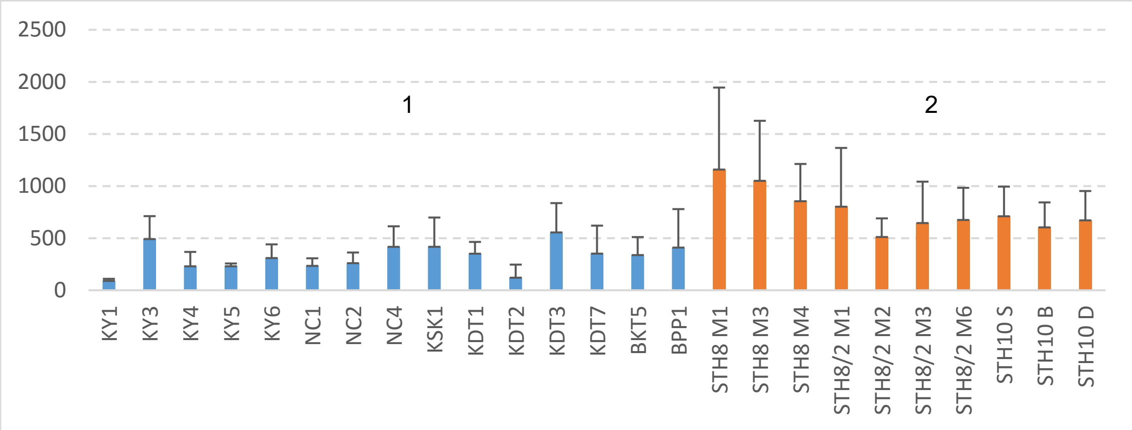


Figure 7.75 Bar chart shows average weight of slag samples from 25 slag deposits. The error bars show the standard deviations. Like in the previous chart, two groups (1 and 2) are suggested by weight.

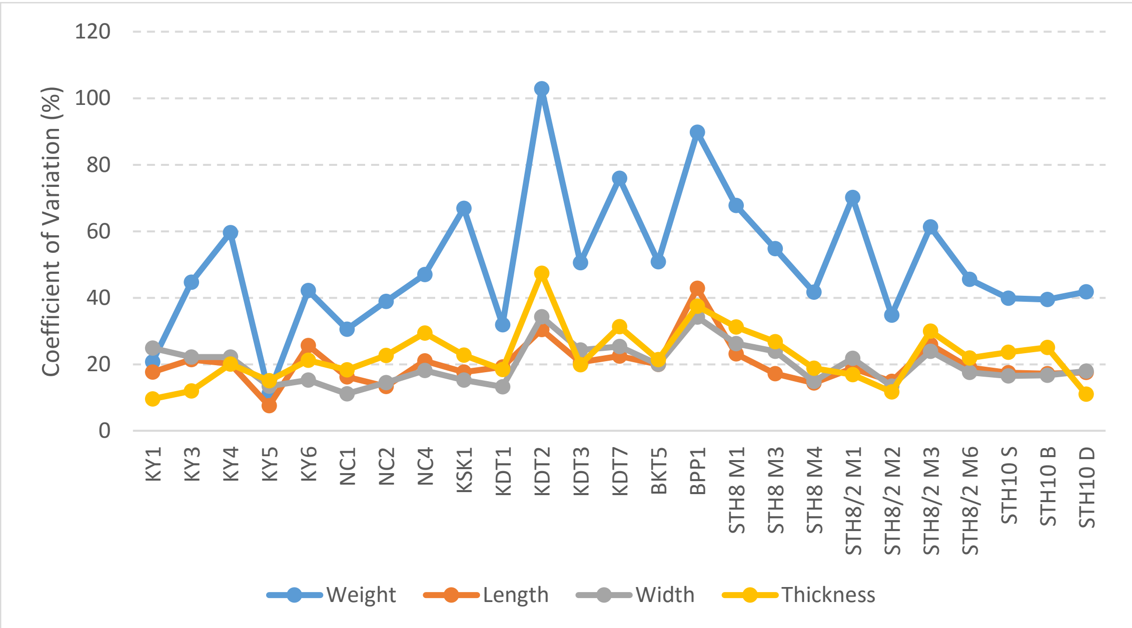


Figure 7.76 Coefficients of variation for sizes and weight of slag samples from 25 slag deposits, calculated from the data shown in Appendix F

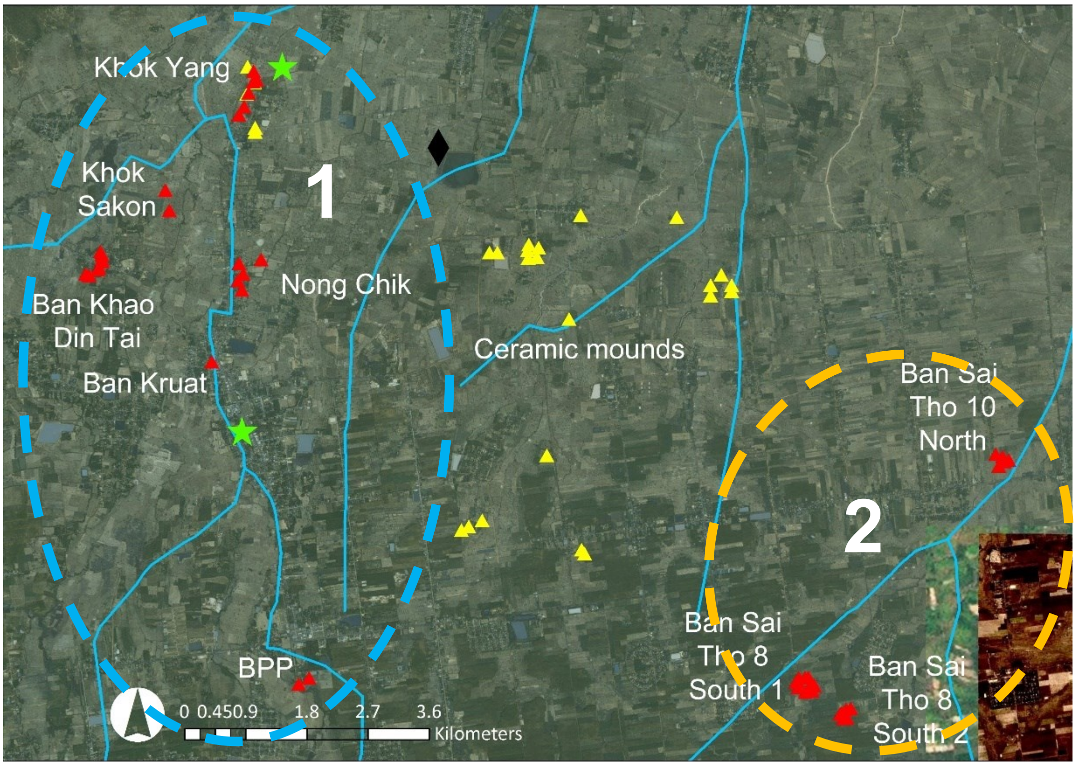


Figure 7.77 Two slag deposit groups (1 and 2), correspondingly to Figure 7.74 and 7.75, suggested by the size and weight data. Slag deposits are marked by red symbols.

Figure 7.78 Three smelting slag subgroups: porous (left), semi-porous (middle), and dense (right)

Slag group	Site	Mass (g)	Volume (cl)	Density
Porous	BKDTKS	1.7	1	1.7
	STH7	5.5	4	1.4
	STH10	3.9	3	1.3
		Average		**1.5**
Semi-porous	BKDTKS	9.2	5	1.8
	STH7	4.5	3	1.5
	BKT	12.8	7	1.8
		7.6	3	2.5
	KDT	11.5	5	2.3
		10.4	5	2.1
	NC	14.3	7	2.0
		3.5	1	3.5
		Average		**2.2**
Dense	KDT	19.3	5	3.9
		16.3	5	3.3
	STH10	11.8	4	3.0
		Average		**3.4**

Table 7.3 Density evaluation of some slag samples from different smelting slag groups. The volume data reported are the differences between the initial volume and volume displaced when a sample was submerged.

The second group is made of convex slag cakes with the sizes ranging from 7cm to 14cm length, 6cm to 10cm width, 4cm to 11cm in thickness, and 288g to 806g weight (Figure 7.45 and 7.79). Their shape (concave/convex (KDT2) and flat/convex (STH8)) and the associated archaeological contexts differentiate this slag from the previous group. The samples have hitherto been found in specific contexts at two excavated sites. At STH8, where the majority of this group of slag came from, this slag type was recovered from the trench at the centre of the mound associated with the probable smithing feature (see section 7.2.7.1). Their particular shape (McDonnell 1983, 1986) and the feature they were associated to, led to the proposal that they may represent smithing slag.

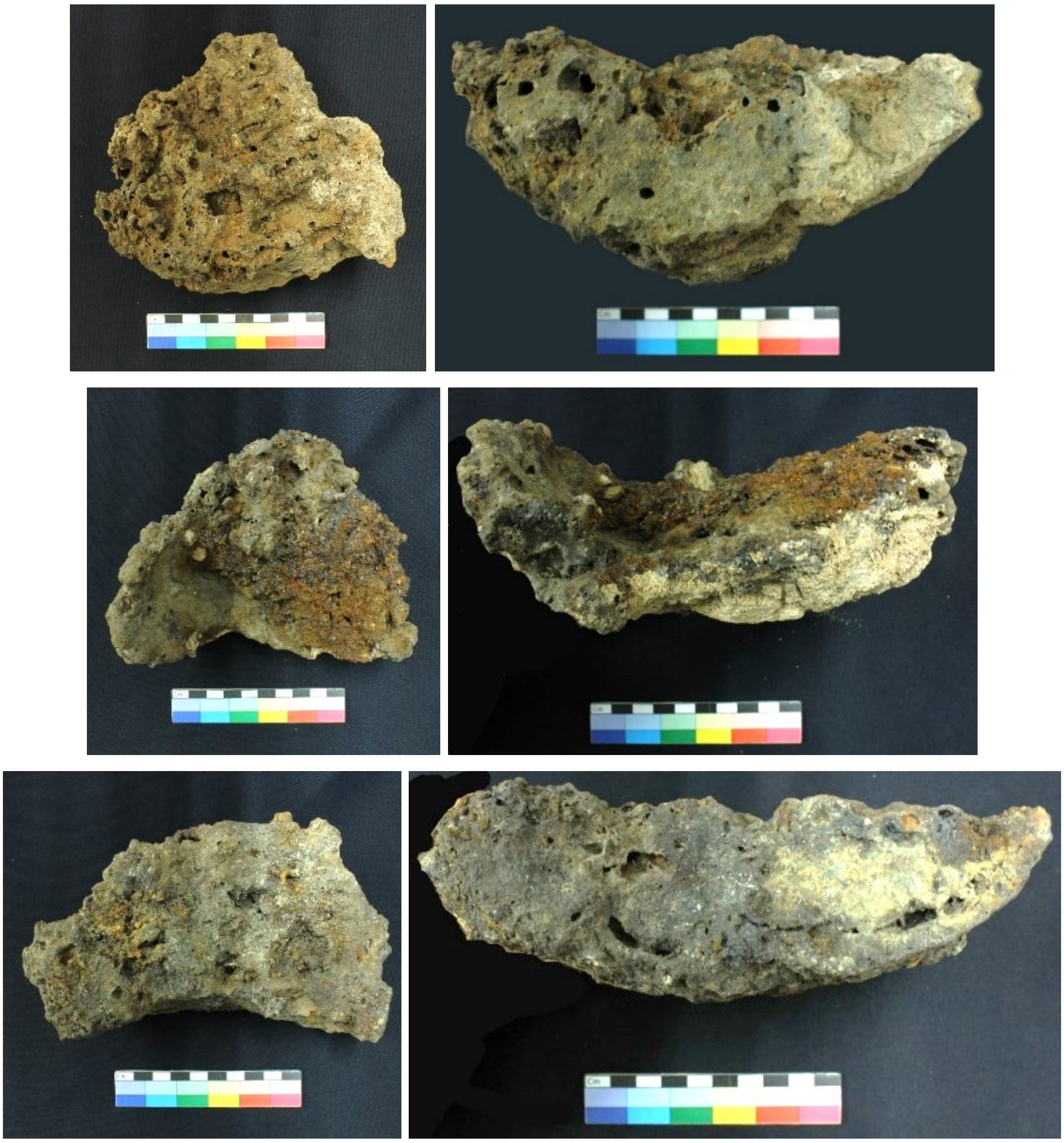


Figure 7.79 Examples of concave/convex shaped slag found associated with the furnace 7 at KDT2 (ventral and lateral view)

The third group concerns rare large slag blocks. They were found in restricted number, six in total, and sites (NC4, KDT2, STH8 M3, and STH8/2 M4). Compared to the first group, they are different as being immensely larger and heavier. Their macrostructure is considered heterogeneous having technical ceramics and/or baked clay trapped in between slag (Figure 7.80-7.83), the feature that has rarely been seen in other slag groups. It is not clear how they were produced, but considering their heterogeneity and attached technical ceramics/baked clay, two possibilities can be proposed. Firstly, they may have been waste from failed smelt. When broken, they macroscopically resemble to some extent typical slag lumps; although, the typical smelting slag rarely has baked clay or broken technical ceramics trapped in the body. These blocks may represent the slag before being moved out of the furnace as smaller lumps. If this supposition is accepted, this means that slag was not tapped out but rather forcibly removed piece by piece corresponding to a lack of flowing pattern on typical smelting slag. The sizes of them are possibly able to fit the sizes, excluding height which is currently unknown, of the reconstructed furnaces at KDT2 (approximately 60-80cm in diameter). There is an exception for the slag blocks found at STH8/2 M4 which are considerably much larger than those at KDT2 and NC4. This leads to the second possibility that the STH8/2 M4 blocks may have belonged to another set of smelting traditions that used furnaces of different sizes. To what extent this possibly indicate a variation in size and shape of furnaces used in Ban Kruat? A detailed microscopic and chemical comparison between them and typical slag lumps, presented in the next chapter, was hoped to clarify these observations.

In African contexts, slag blocks have been also found to be associated with the locations of smelting furnaces and reveal a history of smelting technology and operational episodes involved in producing these blocks when systematically investigated (Humphris 2009; Iles 2011). However, the blocks found in Ban Kruat appear to be moved from their original spots, but, since they were buried, they must have been at their current spots for a while. The removal of one of the blocks at the mound STH8 M3 showed no remains of furnaces underneath, thus, confirming they were moved.

It should be noted that none of slag blocks were cut in half for the systematic sampling (see Humphris 2009; Iles 2011); only fragments from NC4 and STH8/2 M4 were analysed in order to have an overall picture of these blocks and their relationship with local smelting operation. The future works will hopefully revisit and study these blocks systematically.

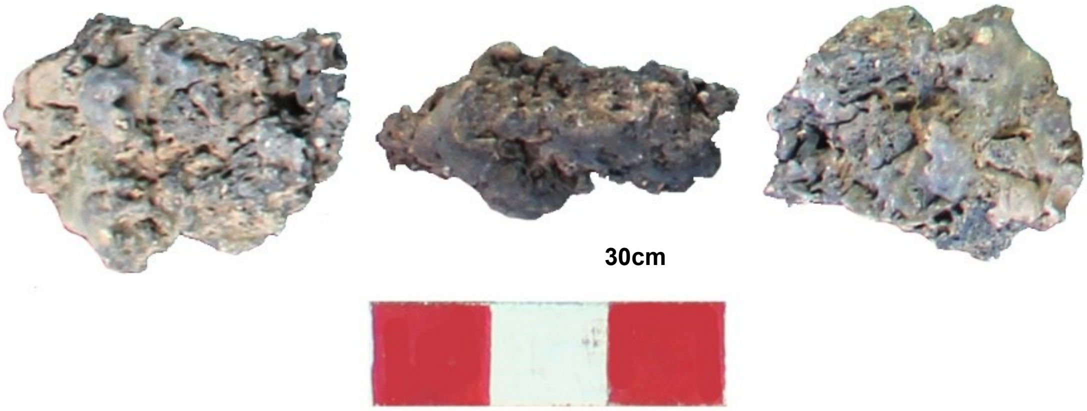


Figure 7.80 Different angles of the sample taken from the slag block found at the mound NC4

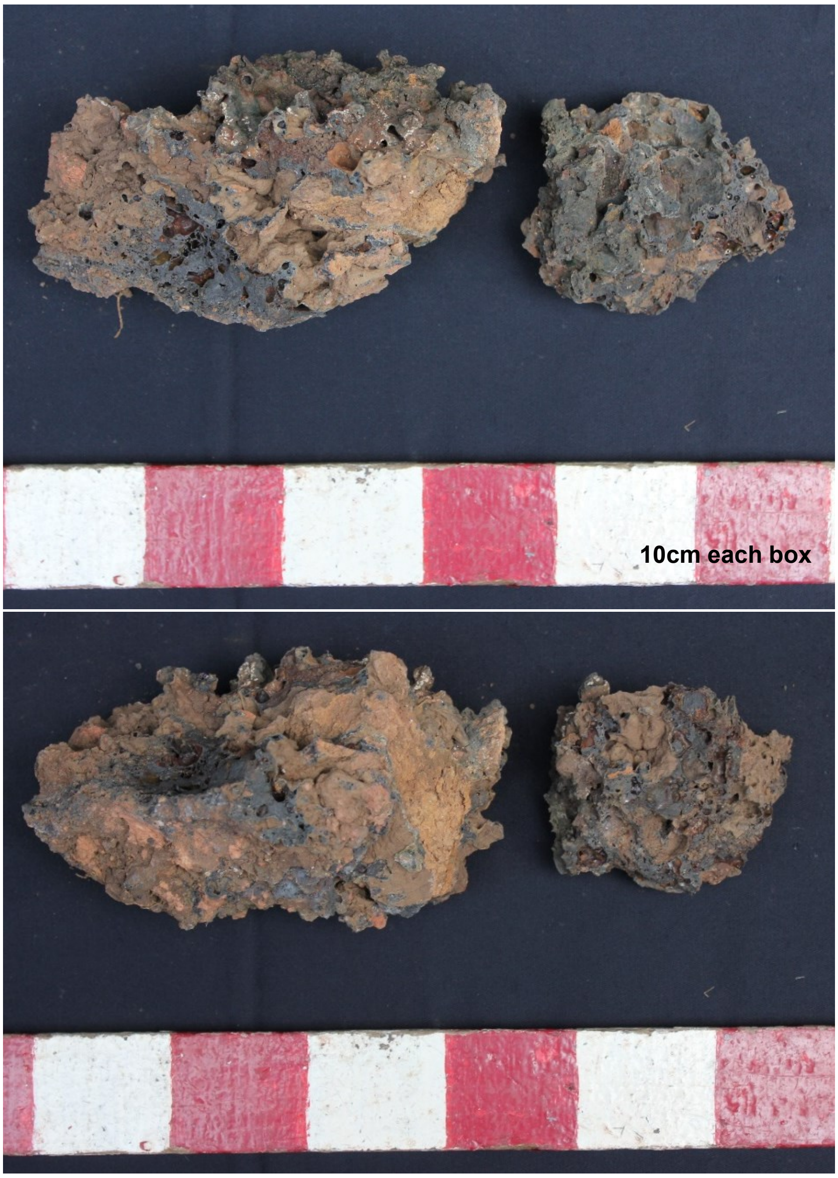


Figure 7.81 Fragments of slag block from the mound STH8 M3

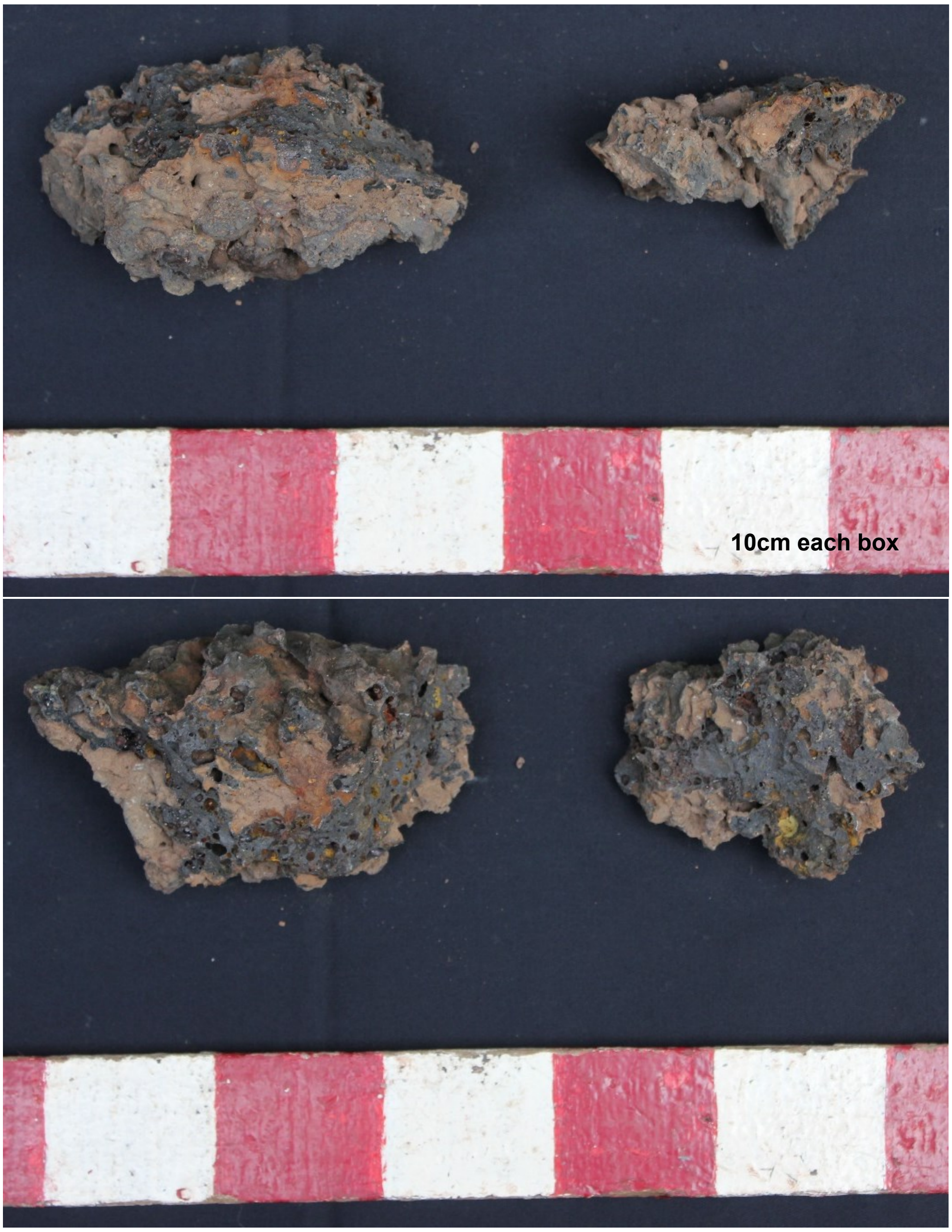


Figure 7.82 Fragments of slag blocks from the mound STH8/2 M4

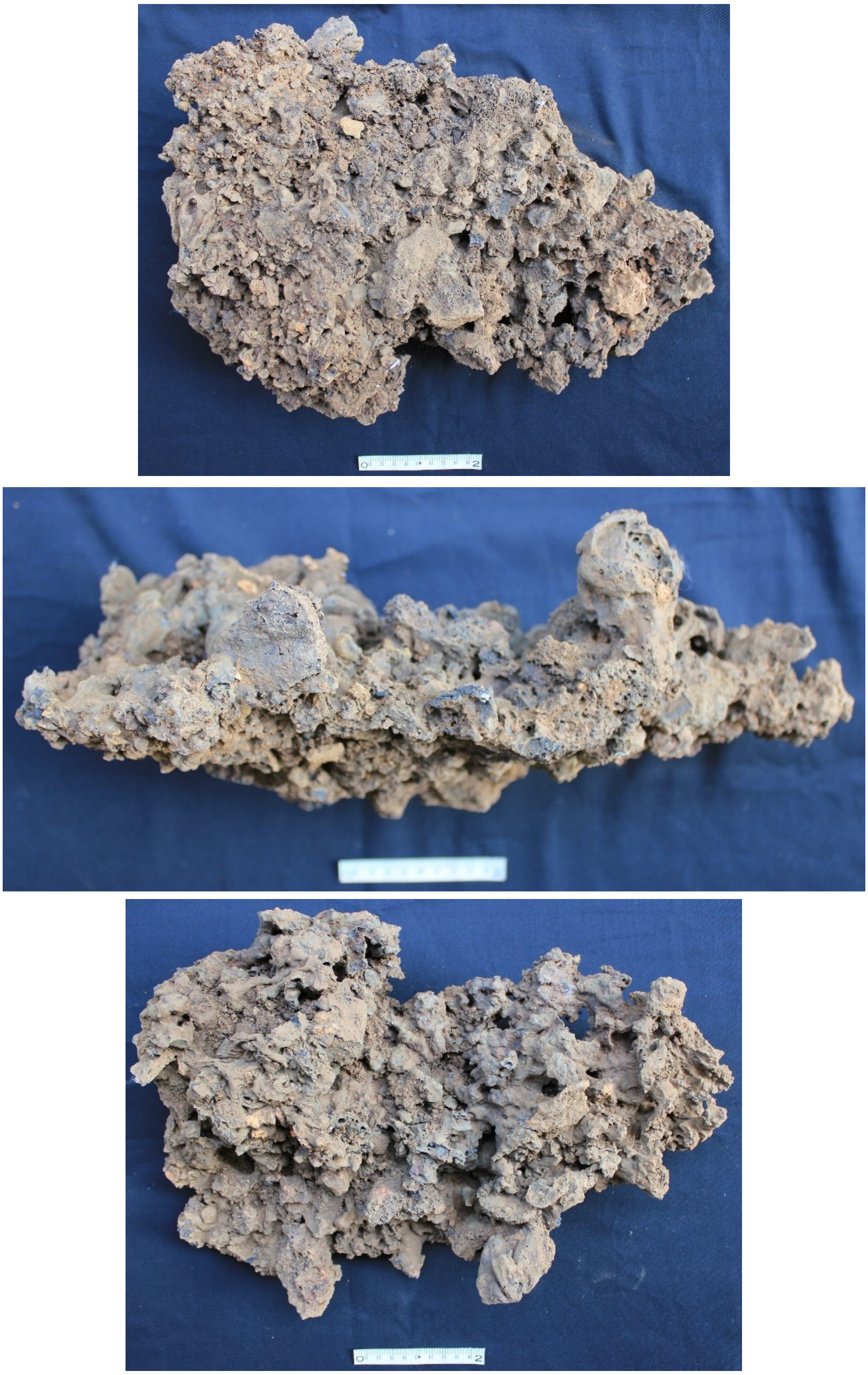


Figure 7.83 Large fused slag found in KDT2 TP2. Scale = 10cm.

7.3.2.2 The technical ceramics

More than 8,500 pieces of technical ceramics were recovered from the excavations at KDT2 and STH8; however, they were not commonly encountered during the surface survey at all slagheaps in 2012. They are mainly fragments making them hard to recognise their original shapes (Figure 7.83), while those in nearly complete conditions are rare and mainly from the excavated collection of KDT2 and STH8 T1 and TP1. The fragments that are still identifiable are akin to those found at Ban Khao Din Tai (see section 7.2.4.1). They include tuyères, clay plugs, and furnace fragments.

Regarding tuyères, almost entirety of the assemblage collected are from the excavations at KDT2 with a few from other deposits (see Appendix D). Nearly complete examples are tuyère nozzles of robust type that were recovered exclusively from the excavations at KDT2 (Figure 7.84). Most of them are structurally intact and often preserve their outer surface which show some features that are informative for understanding the uses of this component in smelting. The front end of the tuyère nozzles clearly shows an overhanging part, where molten ceramic and/or slag material flowed down and was pushed forward by air blast (Figure 7.84). The vitrified layer of molten ceramic and slag, flowing downward, is also seen on the body of some nozzles (Figure 7.21). These features well identify how the nozzles were installed, likely in a downward position, and suggest that these nozzles were in furnace, at least the front end, and directly exposed to high temperature. The expanding part at the back of the nozzles is also often observed which was possibly used to attach to the wall of the furnace (Figure 7.84). Less than five examples can be measured for all dimensions ranging from 12.6-15.3cm in maximum width, 11.6-19.9cm in maximum height, and 4.2-5.6 in maximum thickness. The length is impossible to estimate since no perfectly complete examples have been recovered. Other examples can be measured for some dimensions which the data obtained fit the ranges mentioned previously. Despite their morphological variation, their bore sizes seem to be less variable ranging from 3.6-4.5cm in diameter.

The majority of tuyères are fragments which are identifiable by their characteristic internal curve (bore) (Figure 7.85 and 7.86), but only few of them retain their complete bore shapes, measuring 3.6-4.1cm in diameter (Figure 7.84 and 7.87). Outer surface rarely survives (cf. Hendrickson *et al*. 2012, 9; Suchitta 1983, 110); therefore, their original shapes are currently unclear. Some of the tuyère fragments were possibly once internal part of nozzles, while some may have been tuyères that joined nozzles with bellow (Figure 7.85). Owing to them being incomplete, a comparison between bore diameter and other morphological values (e.g. outer diameter and thickness) could not be done (cf. Pryce *et al*. 2014). Impressions of organic matter (e.g. chaff) are suggestive of type of temper used for manufacturing tuyères.

Although tuyères examined do not show any severe structural degradation caused by high temperature which suggests that clay and temper used are refractory enough to survive high-temperature operation, their structure seems to be friable. Only vitrified and heavily fired parts maintain their integrity, but these layers were often broken off from the body before being recovered (Figure 7.86 and 7.88).

The clay plugs are the only type of technical ceramics that recovered complete during the survey (Figure 7.89). Of nearly complete examples, they are formally comparable to those previously found at KDT2. Their shapes appear to frequently look alike a water drop; however, their sizes significantly vary ranging 9.9-14.6cm in width, 8.6-23.5cm in length, and 4.8-9.7cm in thickness. The previous assumption pointed that they were used to block tapping hole(s) (see section 7.2.4.1); however, the examination of slag associated with this find contradicts it as slag was likely not tapped out of furnace (see section 7.3.2.1). An alternative explanation is that they may have been used to block an observation hole or a hole used for removing slag by other means (e.g. pulling), possibly located between forehearth and furnace proper (Figure 7.27); they may also have served as tuyère stops.

The furnace fragments are the most precarious collection (Figure 7.95). Although they are recognised by their flat shape, very few of them have vitrified layers observed (Figure 7.96). It is possible that this layer might have broken off the bulk of the ceramic after deposition.

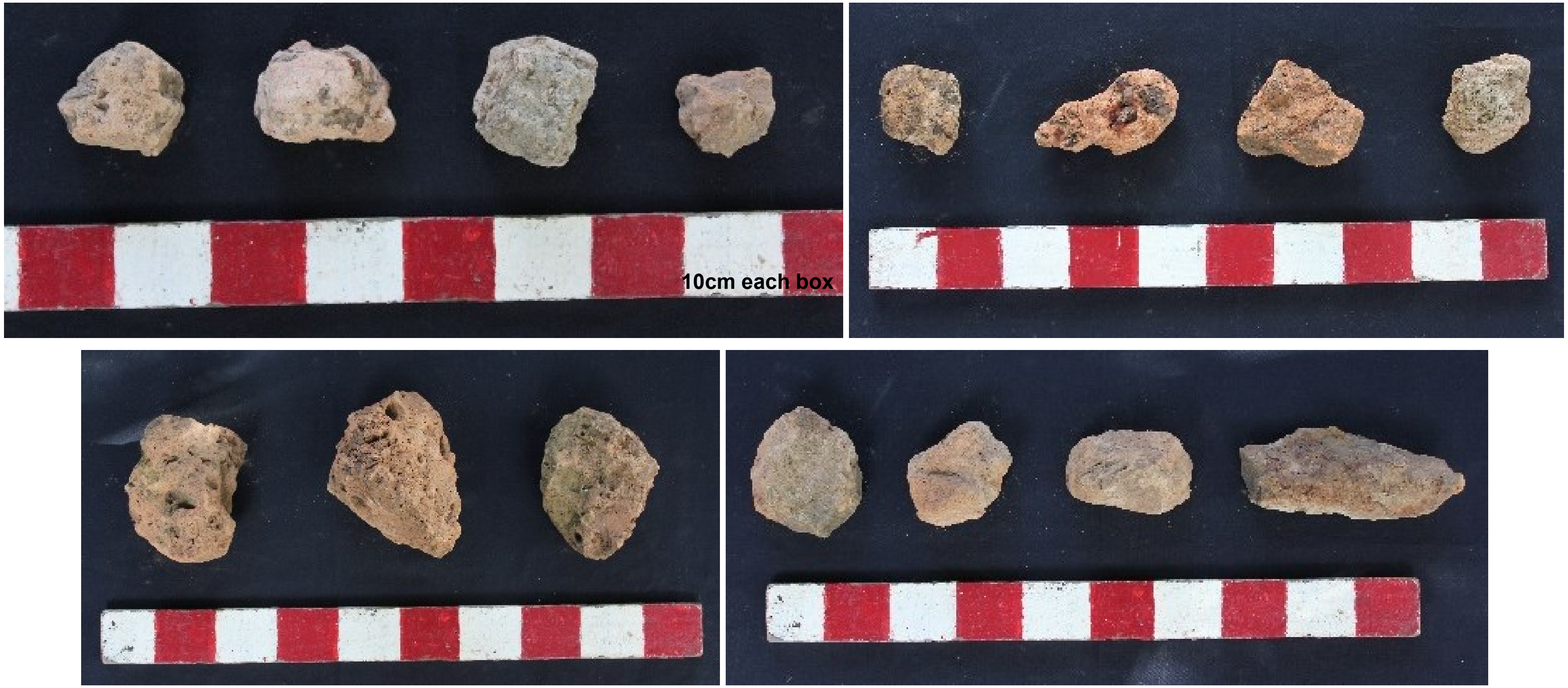


Figure 7.84 Fragments of technical ceramics commonly found associated with slag deposits.

(NC4 (top left), KDT1 (top right), STH8/2 M2 (below left), STH10 B (below right))

Figure 7.85 Examples of most complete tuyères from KDT2. The overhanging part (softened ceramic and/or slag) at the front end of the nozzles and expanding back part, possibly attached to the wall of the furnace are indicated by the numbers 1 and 2 respectively.

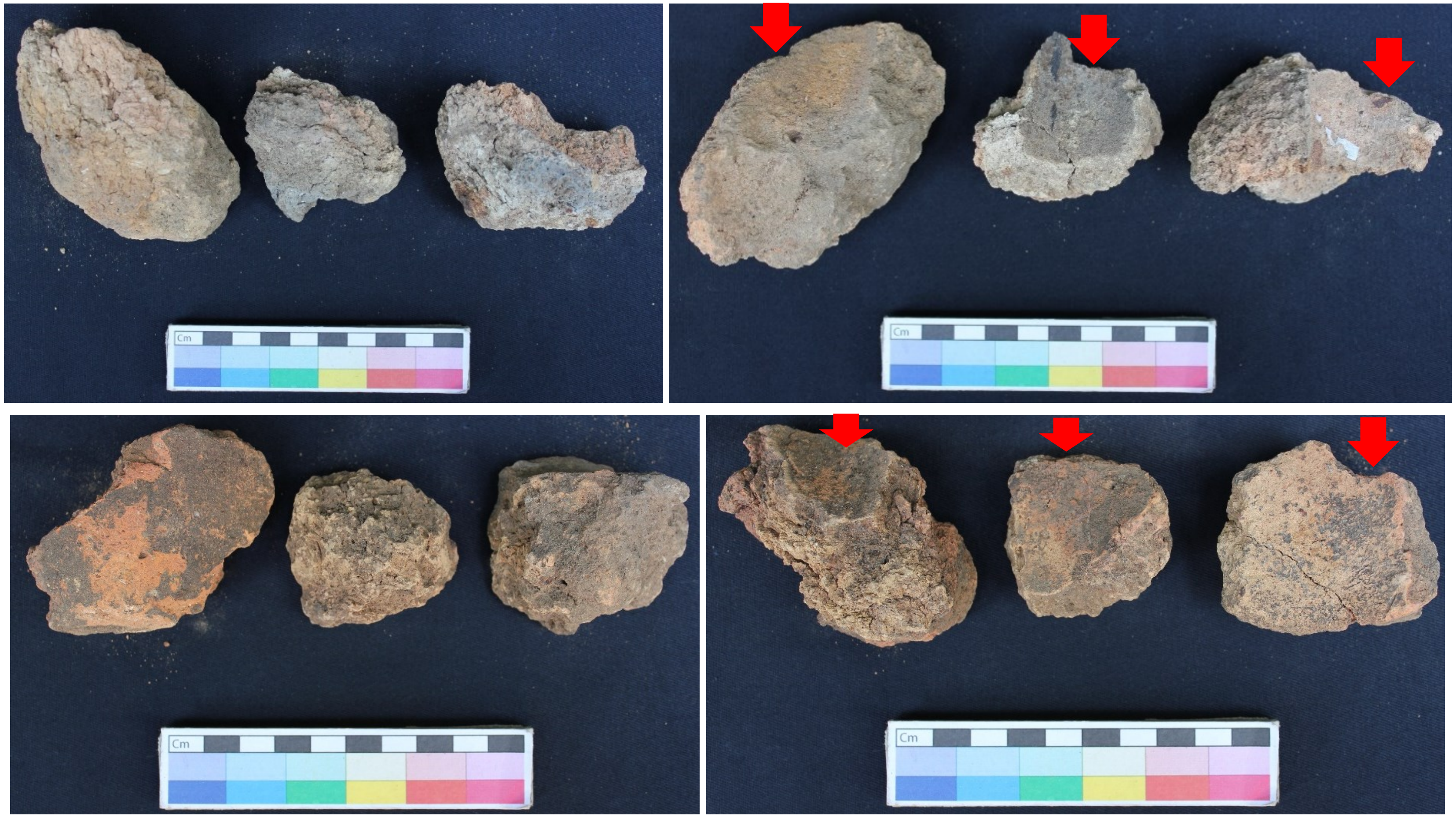


Figure 7.86 Examples of tuyère fragments from KDT2. Red arrows show their characteristic bore. A left sample in below images which has a smooth outer surface may be suggestive of being a tubular tuyère, probably used to join nozzle and bellow. Even though they rarely show a complete outer surface, they seem to be quite thick

Figure 7.87 Other examples of tuyère fragments from KDT2

Figure 7.88 More complete tuyère fragments from STH8 M1 (upper) and STH8 TP1 (below)

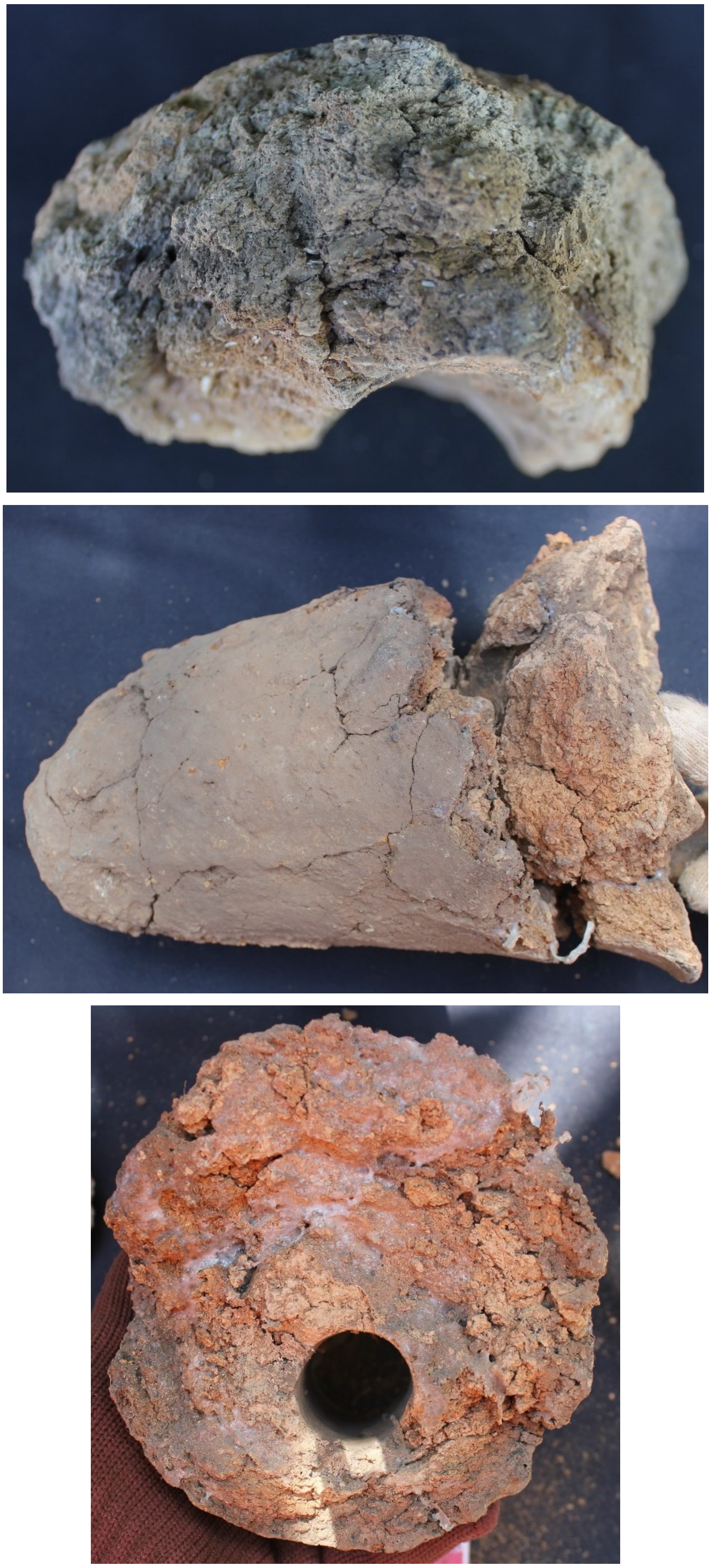


Figure 7.89 Friable structure of tuyères

Figure 7.90 Examples of most complete clay plugs found at STH8 M1 (upper) and KDT2 (lower)

Figure 7.91 Excavated clay plugs from KDT2

Figure 7.92 Clay plug from KDT3

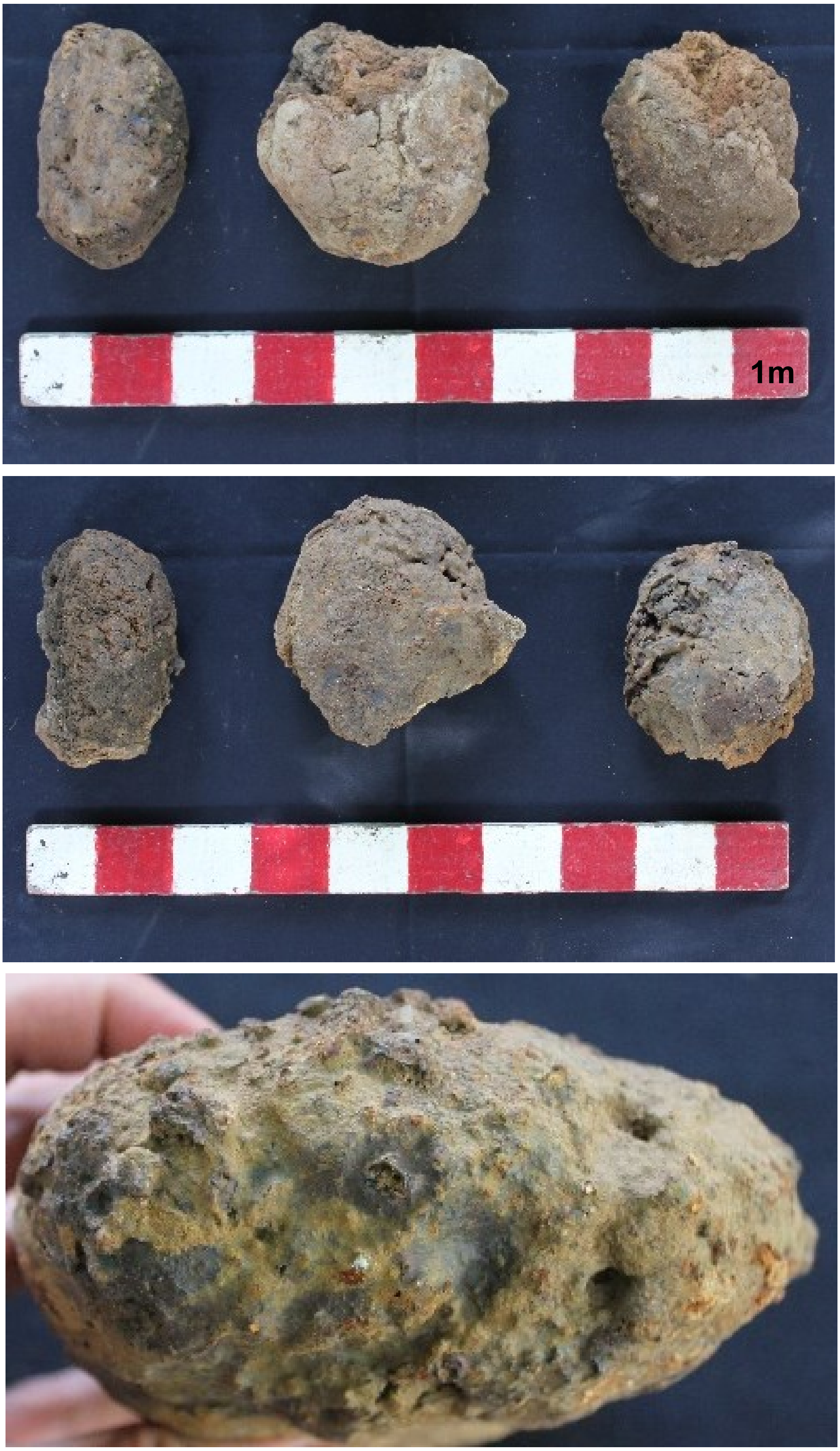


Figure 7.93 Fragments of clay plugs from STH10 S

Figure 7.94 Fragments of clay plugs show their internal structure. The below image shows that outer surface is vitrified as a result of close contact with high temperature.

Figure 7.95 Fragments of the core part of clay plugs suggest that they are quite friable. The below image shows that organic matter was used as a temper.

Figure 7.96 A comparison between the probable furnace fragments from KDT 2 (above) and STH8 M1 (below)

Figure 7.97 Probable fragments of furnace 2 and 5 from KDT2.

7.3.2.3 The laterite samples

Archaeological laterite samples, associated with smelting context, were also securely retrieved from the excavations. The identification of this material on the field was mainly by recognising their relatively reddish clay/stone like nature. Nonetheless, when closely examined, each group: KDT2, STH8, and geological visually shows some discernible features making them different from each other.

At KDT 2, only three samples of conglomerate of pisoliths were collected (Figure 7.24), whereas STH8 yielded more than 30 laterite pieces of various weights (16-39g) (Figure 7.46). Interestingly, the STH8 samples are of a nodular type similar to the laterite suggested as an iron smelting ore in African cases (see section 4.3.3.2). Nonetheless, chemical analysis was needed to ascertain their connection to metallurgy.

The other group of laterite samples collected is from a local geological context. Compared to the previous ones, these samples were from the laterite soils that were dried and solid after being exposed at the surface and became very hard and porous (Figure 7.97). They are likely to have been dug from nearby deposits. Their appearance is very similar to laterite blocks used as building material in the Angkorian period (Figure 7.98).

Figure 7.98 An example of laterite block found locally. This one is carved into a block, possibly for local construction.

Figure 7.99 Laterite blocks used as base of sculpture (top) and building material, mainly as foundation of building (below), during the Angkorian period

7.3.2.4 Initial hypotheses on technology and spatial organisation

The preliminarily visual observation of the sites and the materials recovered indicates that they are largely comparable. None of the sites visited stands out as yielding considerably distinguishable remains to suggest a new group or site type. The only exception is the fact that the purported smithing slag (plano-convex slag) was only recovered from excavation, but this most likely reflects the comparatively lower abundance of these remains on a surface level, which are therefore harder to recover during surface surveys. On this basis, the overall impression derived is that all sites represent remains or products from very similar practices. This is quite interesting as this collective similarity may represent a continuity of similar practices throughout a long chronology.

Overall, the information gathered so far points to a landscape dominated by bloomery iron smelting slag produced in non-slag-tapping furnaces. Laterite is hypothesised as a potential ore. Most likely, two activities are documented: smelting of ores into blooms, and probable primary smithing of these to consolidate them into billet or bar form. The bulk of the slag deposits are highly likely to derive from smelting activity, while smithing evidence only appears at STH8 and, possibly, KDT2 in a small quantity. Robust tuyères were used to feed air into the furnace, and clay plugs employed to block the lower arch of the furnace when required. It is possible that air tuyeres connected to a robust nozzle were also employed at the smithing hearths, but this extent is quite difficult to verify given the fragmentary nature of the evidence. At present, there seems to be no evidence for ore processing and secondary smithing at the sites, although of course this does not preclude the possibility that these activities – especially the former – took place in the area.

Further conjecture concerns the possible spatial organisation of workshops. This stems from the observation of the remains at STH8. It is quite certain that the surrounding mounds is likely to have been linked to the smelting activity. Contrastingly, the central area might have been associated with the smithing activity. Accordingly, one may assume an organisation of the working spaces. As mentioned previously, this site pattern concerning the ring of mounds enveloping the crater has not been reported elsewhere in Thailand. This kind of a spatial organisation is seen at the iron production site in Fiko, Mali, where slag heaps were formed surrounding the smelting area (Perret and Serneels 2009, 1-2), but, as discussed above, the preliminary observation of the remains at STH8 has suggested that this may not be the case. Furthermore, the case may have been

different from KDT2, where the smithing activity might have been conducted at the same location as the smelting.
Looking at the broader pictures, metallurgical evidence in Ban Kruat shows some similarities and distinctions compared to other iron production remains found elsewhere (see section 4.3). The presence of laterite ore associated with Ban Kruat iron production remains fits a long-standing proposal of laterite smelting in lower Northeast Thailand (see section 4.3.3). However, despite smelting similar ore, Ban Kruat seems to have followed its own production traditions as demonstrated by distinctive types of tuyère nozzles and clay plugs that have never been reported in lower Northeast Thailand or other sites in mainland Southeast Asia.

The results of the laboratory-based investigation presented in the following chapters will allow, from the perspectives of micro- and chemical compositional analysis, an assessment of the propositions presented above and provide further insight into the technical parameters of the metallurgical activities. Furthermore, they are hoped to facilitate detecting any differences or variations that macroscopic examination cannot achieve.

7.4 Summary

The recent survey identified only 47 slag deposits out of the 67 sites reported by LARP; the decreasing number of sites might be due to the re-definition of slag deposits by the author and inaccessibility of sites, especially Ban Kruat cluster where only one of 11 sites could be visited. Some sites, such as NC4, KDT3, and STH8/2 are evident that they were recently disturbed, in particular KDT3 where slag was used for road construction. In a broad sense, this recent investigation confirms the points made by previous work regarding the abundance, typical layout, and main technological origin of the sites (Tanlasanawong *et al.* 2007; Lertlum *et al.* 2008, 2010; Yoopom 2010; Venunan 2011), while at the same time it refines the range of hypotheses that can be tested through a technical analyses. Moreover, a particularly noteworthy finding of this reassessment concerns the chronology, since metallurgical activities at both excavated sites have been shown to start in the Iron Age, thus challenging previous assumptions of later dates. This chapter concludes by highlighting some key observations emerging from the previous pages, which will be useful points of reference for the discussion presented in Chapter 8 and 9.

Firstly, no potential areas for the smelters' settlements have hitherto been located. Thus, it is uncertain whether there was one large commune of smelters or various settlements attached to each cluster, or indeed whether smelters travelled from elsewhere to this location on daily basis or perhaps seasonally. Nevertheless, a consideration of the typical Angkorian Khmer settlement pattern might provide a useful foundation to propose a possible scenario, especially if we accept the proposition that the peak of the activity would have taken place during this period.

Secondly, a chronological framework cannot be fully resolved for all slag deposits. Given the scarcity of datable finds or reliable dates, it was hoped that technological data might allow this work to distinguish groups according to their technical practice, which might provisionally be assigned to different time periods. However, the overall impression based on the macroscopic assessment is one of broad similarities rather than significant differences. If this internal coherence is confirmed in the technical analysis, it could be taken as indicative of continuity in technological practice.

Lastly, it is quite interesting to witness a similar metallurgical assemblage across slag deposits. This similarity may be suggested of them being from the similar practices. Another related aspect to be investigated concerns, as mentioned at the beginning of this chapter, the origin and continuity of this technology. The further laboratory-based archaeometallurgical examination on the remains and the comparison with other iron production evidence of preceding and Angkorian periods would clarify both aspects being raised here.

Chapter 8 Laboratory analysis of the Ban Kruat iron production remains and its technological implications

8.1 Introduction

The macroscopic investigation of Ban Kruat metallurgical remains presented in the previous chapter indicated that iron smelting and probable primary smithing operations may have been associated with the exploitation of local laterite sources. Based on the similarities observed during visual inspection, slag and technical ceramics seem to originate from very similar ironworking traditions. Compared with wider technological contexts in mainland Southeast Asia, the findings have posited that Ban Kruat smelting traditions share some technical attributes with other ancient iron smelting in lower Northeast Thailand (e.g. the use of laterite as an ore). At the same time, Ban Kruat metallurgical remains also exhibit distinctive technical features (e.g. large tuyère nozzles and clay plugs) that have not been documented elsewhere in this region.

The new data generated from this first stage challenged previous technological reconstructions and provided fresh interpretation and contextualisation for the technical and socioeconomic context of local iron production. Yet these initial findings only clarified and answered the research questions to a limited extent, and they need to be reassessed to ensure their plausibility. Moreover, these data alone do not allow a detailed technical reconstruction of the ironworking processes and inferences about broader issues such as scale and organisation. For these reasons, this chapter focuses on the detailed characterisation of metallurgical remains through structural and chemical analysis. The mineralogy and the chemical composition of the potential ore and slag are used to evaluate the hypotheses proposed in Chapter 7. Technical parameters and variability in ironworking processes can also be better explored through a consideration of these laboratory data. They include the relations between each component (e.g. laterite and technical ceramics) in the smelting system which produced the resultant slag (slag formation), the estimation of operating conditions of Ban Kruat ironworking traditions, and technical variability within and between slag deposits. Data generated also help develop some thoughts on the production of technical ceramics. Altogether, these parameters allow this research to identify choices and constraints framing this technology. The information obtained will enable a technical cross-comparison between Ban Kruat and laterite smelting locales in Africa and other known ancient ironworking cases in mainland Southeast Asia.

As stated in Chapters 5 and 7, the sampling sought to cover all the metallurgical components introduced into the ironworking operations, i.e. laterite ore, technical ceramics (tuyères, clay plugs, and furnace fragments), and slag (smelting and probable smithing slag)). Charcoal fragments associated with smelting were not sampled since most of charcoal samples found were very small (less than 1-2g), usually trapped in the pores inside smelting slag, and large ones have been preserved for dating determination.

To properly analyse this material, an analytical instrument such as ICP-AES may be a more suitable choice than XRF, which was employed in this research, due to lower detection limits and smaller sample size requirement. Moreover, one may argue that charcoal ashes can be widely variable in composition, depending on the species and season when they are harvested. The samples were selected from 13 out of 24 sites which are KY4, NC4, KSK1, KDT (1, 2, and 3), BKT5, BPP, STH8 (M1, M2, and central area), STH8/2 M6, and STH10S (see section 5.1.2 and section 7.2 for the selection of the sites). In total, 166 samples were analysed (see Appendix D for a summary of the samples included). Please note that throughout this chapter each sample is shown by its corresponding codename. For example, KDT2e002 is the laterite sample 002 from KDT2, and KDT1-007 is slag number 007 from KDT1. Their full information (names and contexts) can be found in Appendix H.

8.2 Organisation of this chapter

The initial assessment of the assemblages showed that differences between sites examined were largely insignificant (section 7.3.2). This homogeneity was verified by the technical analyses. Hence, in order to avoid reporting repetitive analytical results on a site by site basis, this chapter starts by illustrating this uniformity, in order to justify the subsequent reporting of the analytical results together in a single chapter. Of course, this uniformity is archaeologically significant, and will be discussed in later in this chapter.

Firstly, the mineralogy of the samples (eight laterite samples, six technical ceramic samples, and 63 slag samples) is considered. Though full results will be discussed later, it is proposed here that the samples in each material group largely share similar microstructures (Figure 8.1-8.4).

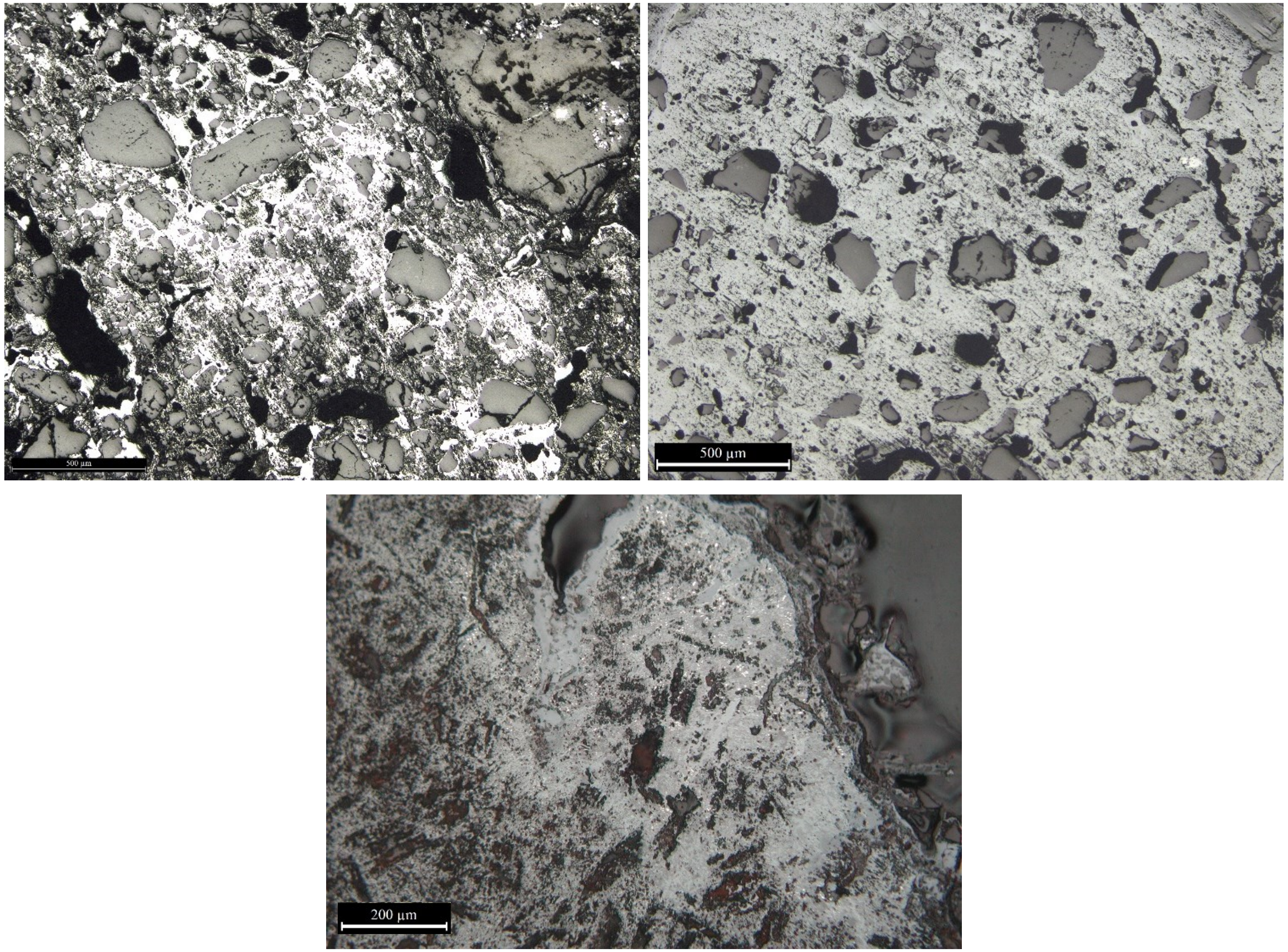


Figure 8.1 Micrographs of some laterite samples (BBPLAT, STH8e002, and KDT2e002). Laterite samples are microstructurally quite heterogeneous internally, although their structure can largely be divided into three major parts: the quartz-rich area, quartz/iron oxide area, and iron oxide-rich area (described in detail in section 8.3.1). These images show exclusively the iron oxide-rich area of the samples, showing in all cases a matrix of iron hydroxides interspersed by mineral inclusions.

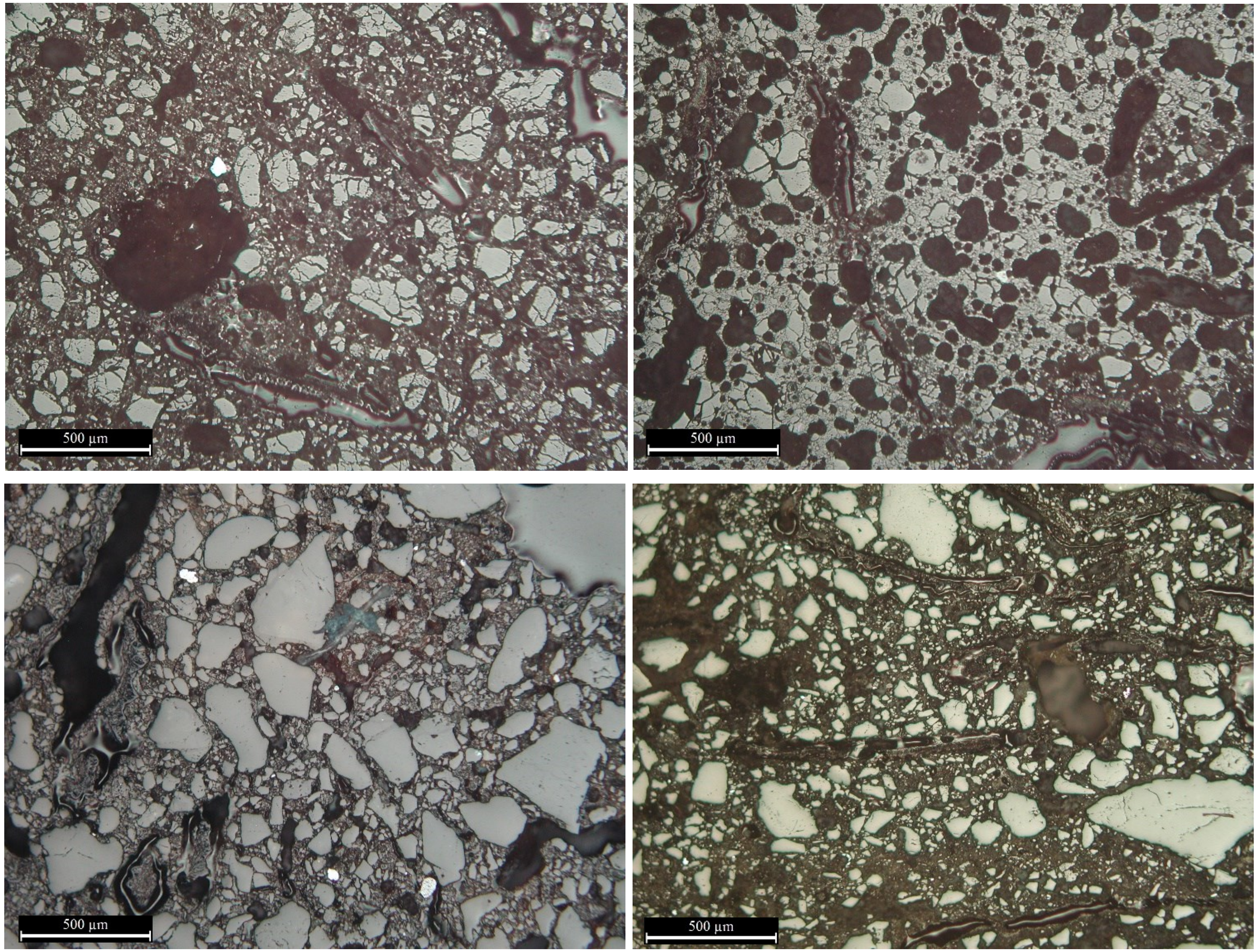


Figure 8.2 Micrographs of some technical ceramic samples (KDT2CP002, KDT2CP001, KDT2FF003, KDT2FF002). Microstructurally, quartz and elongated voids can be observed interspersed within clay matrices.

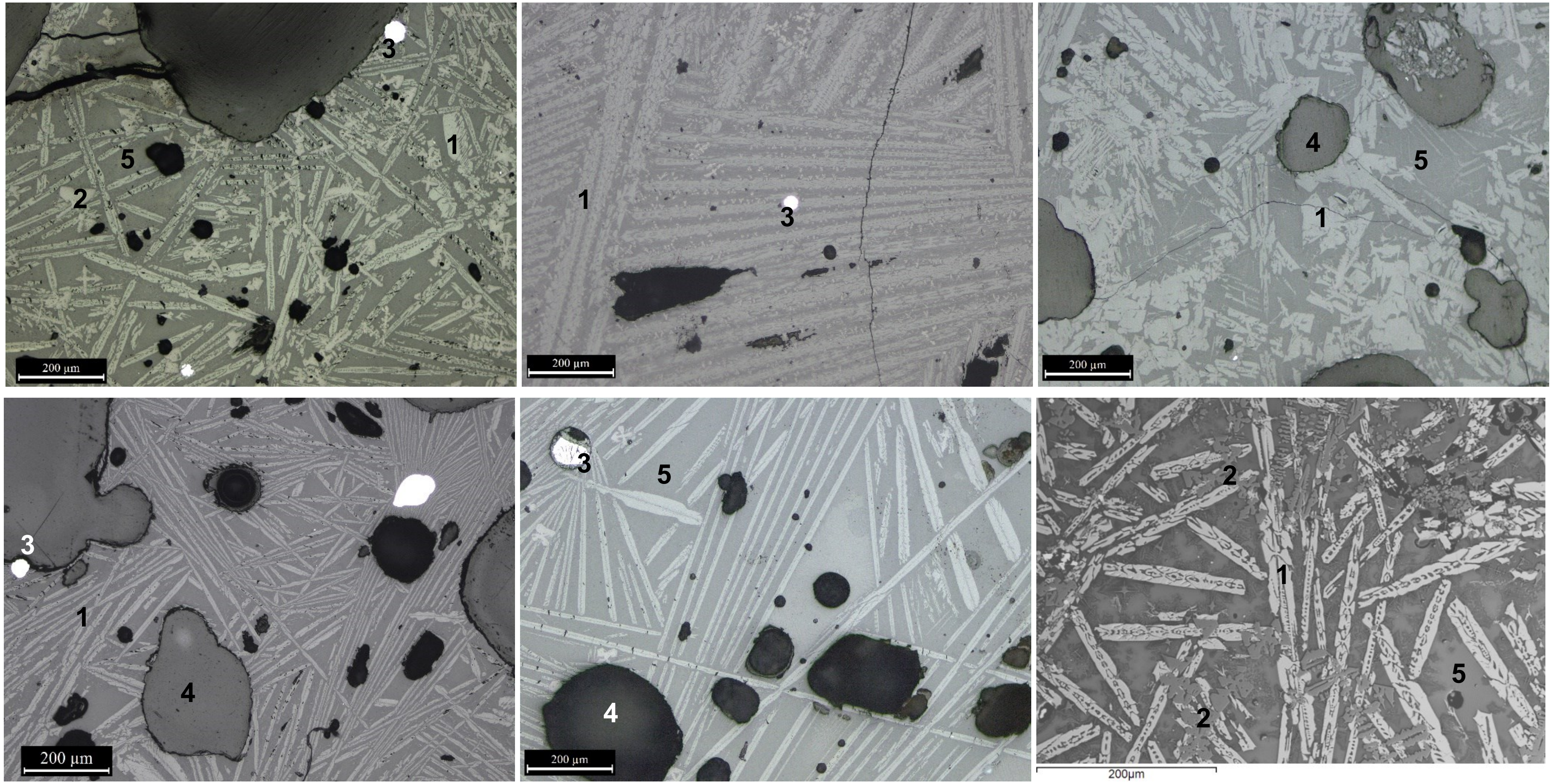


Figure 8.3 Micrographs of some smelting slag samples from NC4, KDT2, BKT5, STH8 M1, and STH10S. Their microstructure consists of elongated fayalite (1), hercynite (2), relatively round iron particles (3), relatively abundant porosity (4), and glass matrices (5). The BSE image of the KY4 sample provides a better illustration of hercynite which is hard to see under reflected light. See the detailed descriptions and larger images (high magnification) in section 8.3.3.1.1.

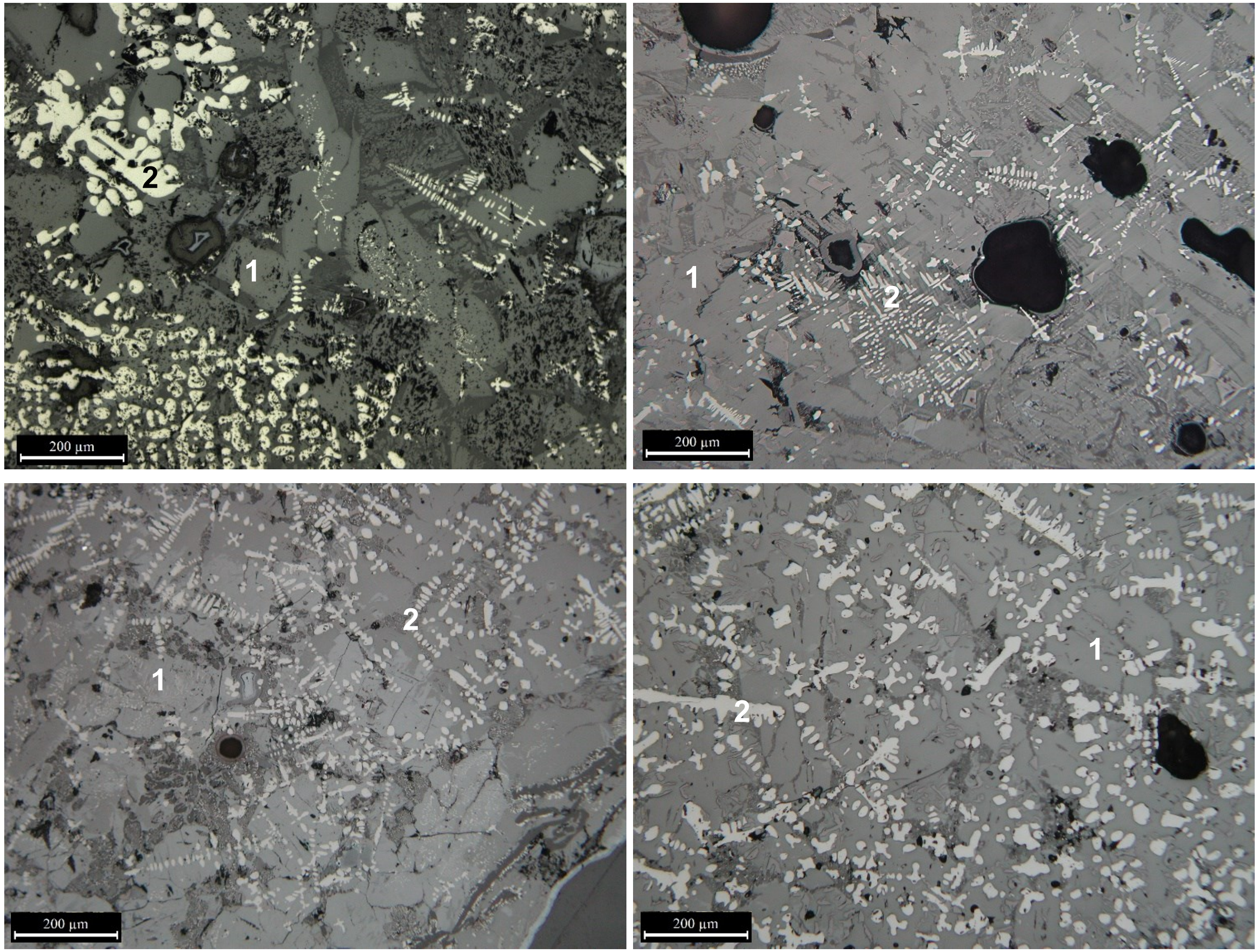


Figure 8.4 Micrographs of some smithing slag samples (STH8sm004, STH8sm003, KDT2/7-001, and KDT2/7-006). Their microstructure is characterised by blocky fayalite (1), wüstite (2), and glass matrices, which can be better seen in higher magnification (see section 8.3.3.2).

The structural similarity within sample groups has a correlation in their chemistry. This is illustrated by plotting the WD-XRF results in a ternary diagram of the FeO-SiO_2-Al_2O_3 system (Figure 8.5). The plot clearly shows that the samples form clusters according to their material groups regardless of their context. An exception can be seen in the laterite samples, which display larger chemical heterogeneity, as discussed in section 8.3.1. The slag samples are divided into the two main groups, representing smelting and smithing slag. Interestingly, the smelting slag samples cluster tightly in one particular area. No clear subgroups can be observed for the technical ceramic samples.

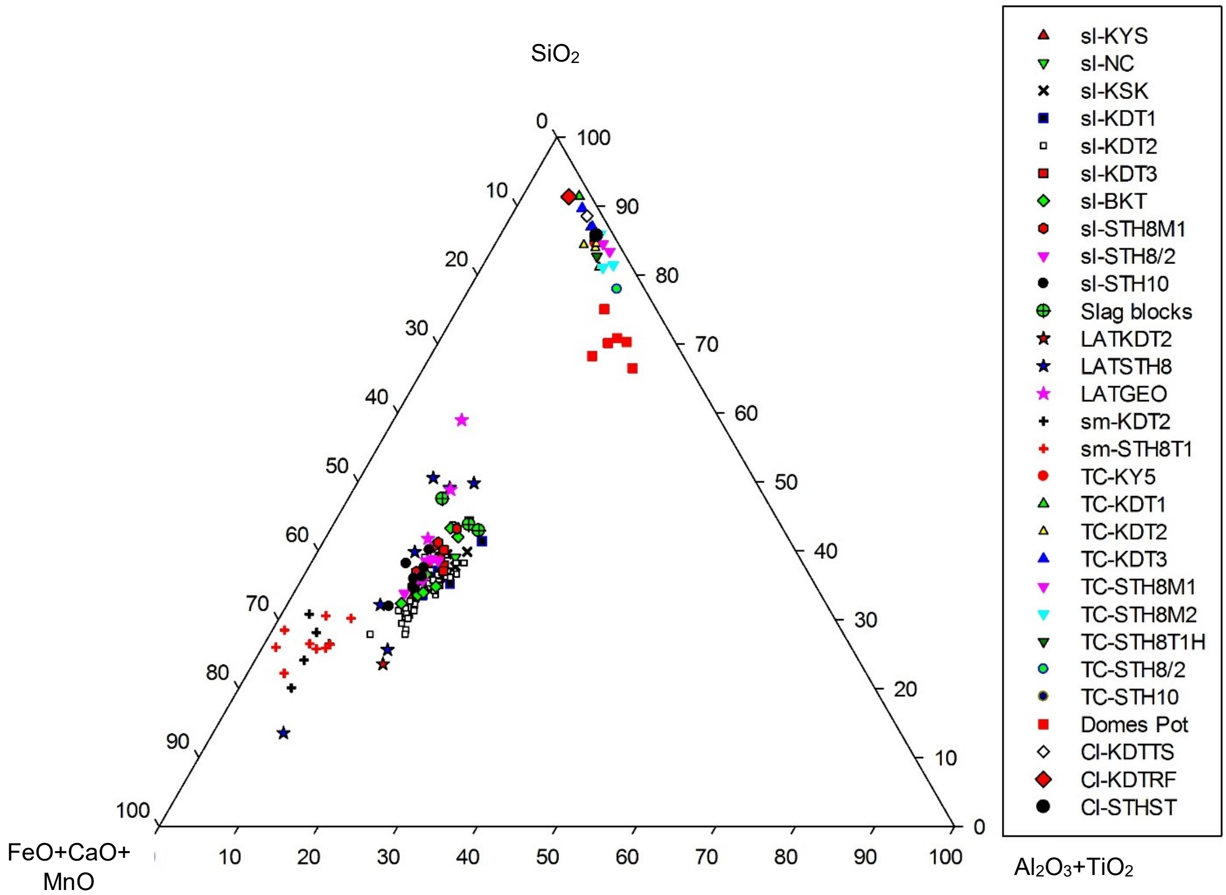


Figure 8.5 A ternary diagram of the $FeO(+CaO+MnO)$-SiO_2-$Al_2O_3(+TiO_2)$ system shows all samples analysed, calculated using normalised WD-XRF data. Legend: sl-smelting slag, LAT-laterite, sm-smithing slag, TC-technical ceramics, Domes Pot-domestic pottery, and Cl-clay sample

The appearance (see also section 7.3.2), microstructures, and chemical compositions of the studied samples indicate that they were produced using very similar recipes. Therefore, this chapter is organised by materials rather than by sites. Lastly, it should be remembered that only KDT2 and STH8 T1 are radiometrically dated to the late Iron Age (3^{rd}-6^{th} century AD); the others have yet to be dated (see section 7.3.1.3). The interpretations therefore concern a general characterisation of metallurgical technologies in Ban Kruat, regardless of their chronologies.

8.3 Analytical results and discussion

8.3.1 Laterite samples: archaeological and geological

Thirty five laterite samples associated with iron production contexts, exclusively from KDT2 and STH8 T1 and T2, were identified during LARP archaeological excavations. Although they were found in reliable contexts and are likely to be ore fragments, they may have been rejected, due to their poorer quality, or dropped accidentally while charging the furnace. Geological samples from three locations in Ban Kruat were also collected to investigate the nature of laterite in local geological contexts (STH8-6LAT (see section 7.2.7 for the information about the location for sampling), BPPLAT (see Figure 7.36 for the location for sampling), and BKTLAT (given to the author by local researcher, told to be from the area within the Nong Chik village)). Macroscopic examination divided them into three main groups according to their appearance: conglomerate of pisoliths (KDT2), nodules (STH8), and consolidated laterite soils (geological laterite) (see section 7.3.2.3). This might suggest specific preferences for certain kinds of laterite used for iron smelting; however, the information obtained is insufficient to approach this question.

More information was further extracted from the selected samples through laboratory analyses (OM, SEM-EDS, XRD, and WD-XRF): two archaeological samples from KDT2, six from STH8, and three geological samples (not analysed by XRD).

8.3.1.1 Further characterisation of laterite samples

Two samples from KDT2 belonging to the first group are dark red (KDT2e001) or reddish brown (KDT2e002) in colour and in the form of a conglomeration of small pisoliths (a concentric accretion of rock or mineral) held together by clay/quartz materials (Figure 8.6). A cross-section of KDT2e002 exhibits the formation of this material where pisoliths are cemented together into a bigger piece. The dark purple colour of pisoliths' profiles is reminiscent of the characteristic colour of magnetite (Figure 8.7). Judging by its morphology, they might come from a laterite crust in which the nodules concentrated. The microstructural examination of the same sample confirms these observations (Figure 8.8-8.10). The chemical analysis of some pisoliths using SEM-EDS (Table 8.1), particularly those with more concentrated white areas (in both reflected light and BSE), shows the levels of FeO between 59 and 70 wt%, and significantly high levels of Al_2O_3

between 15-24 wt%. Levels of P_2O_5 and TiO_2 are quite consistent, 1.2-1.6 wt% and 2.1-2.9 wt% respectively; although, some pisoliths can have considerably higher P_2O_5 (Table 8.1). Clay/quartz regions, which are supposedly clay-like materials holding different pisoliths together, also contain a relatively high level of Al_2O_3 (14 wt%). This possibly implies that not only pisoliths that are rich in alumina but also the clay material in between each pisolith. MgO and K_2O in low contents are seen to be associated with these regions rather than in pisoliths.

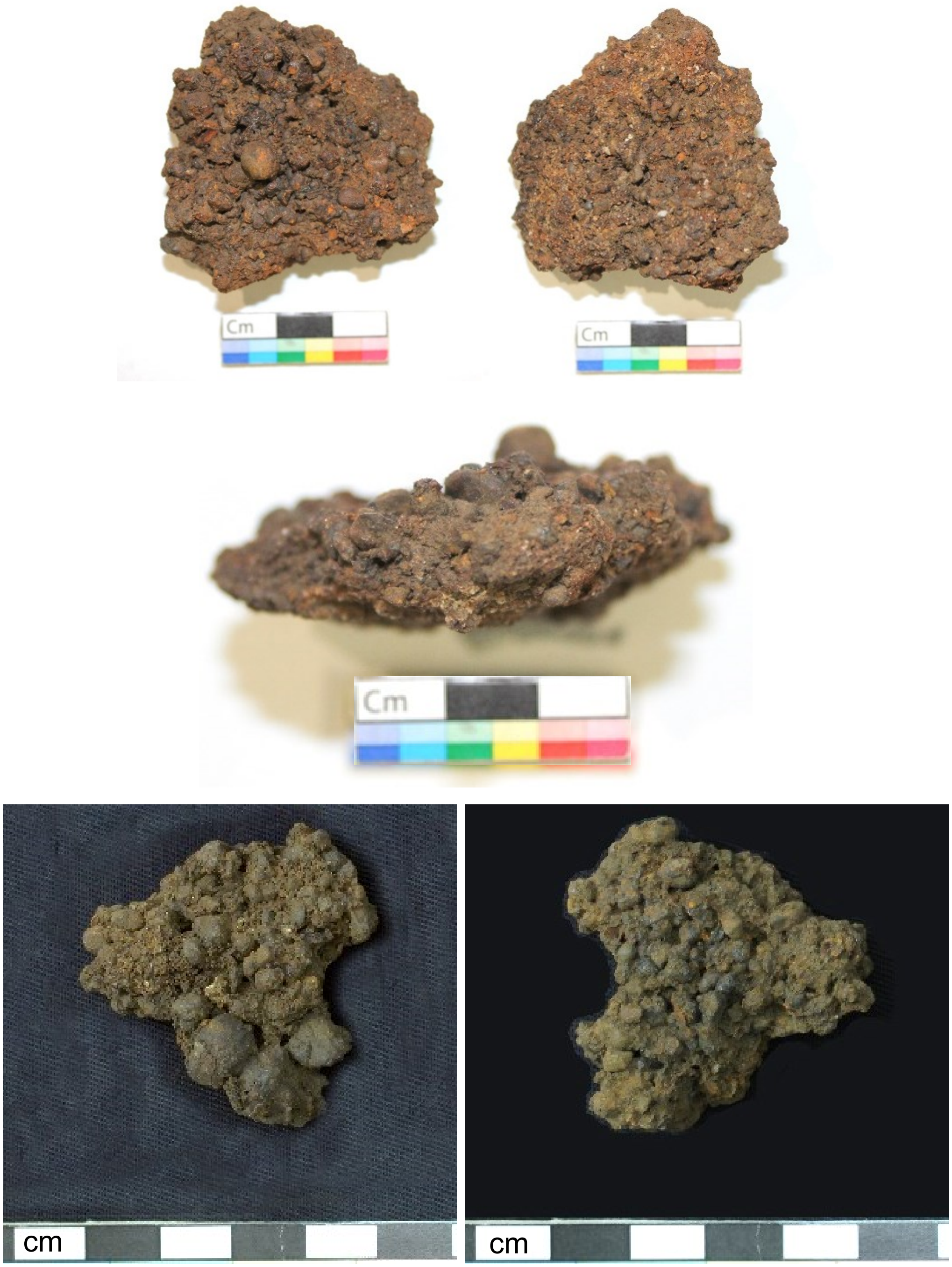


Figure 8.6 Laterite samples from KDT2 (KDT2e001 (top) and KDTe002 (below)).

Figure 8.7 The profile of KDT2e002 shows a cluster of small nodules cemented by some geological materials

(Image width ≈ 1cm)

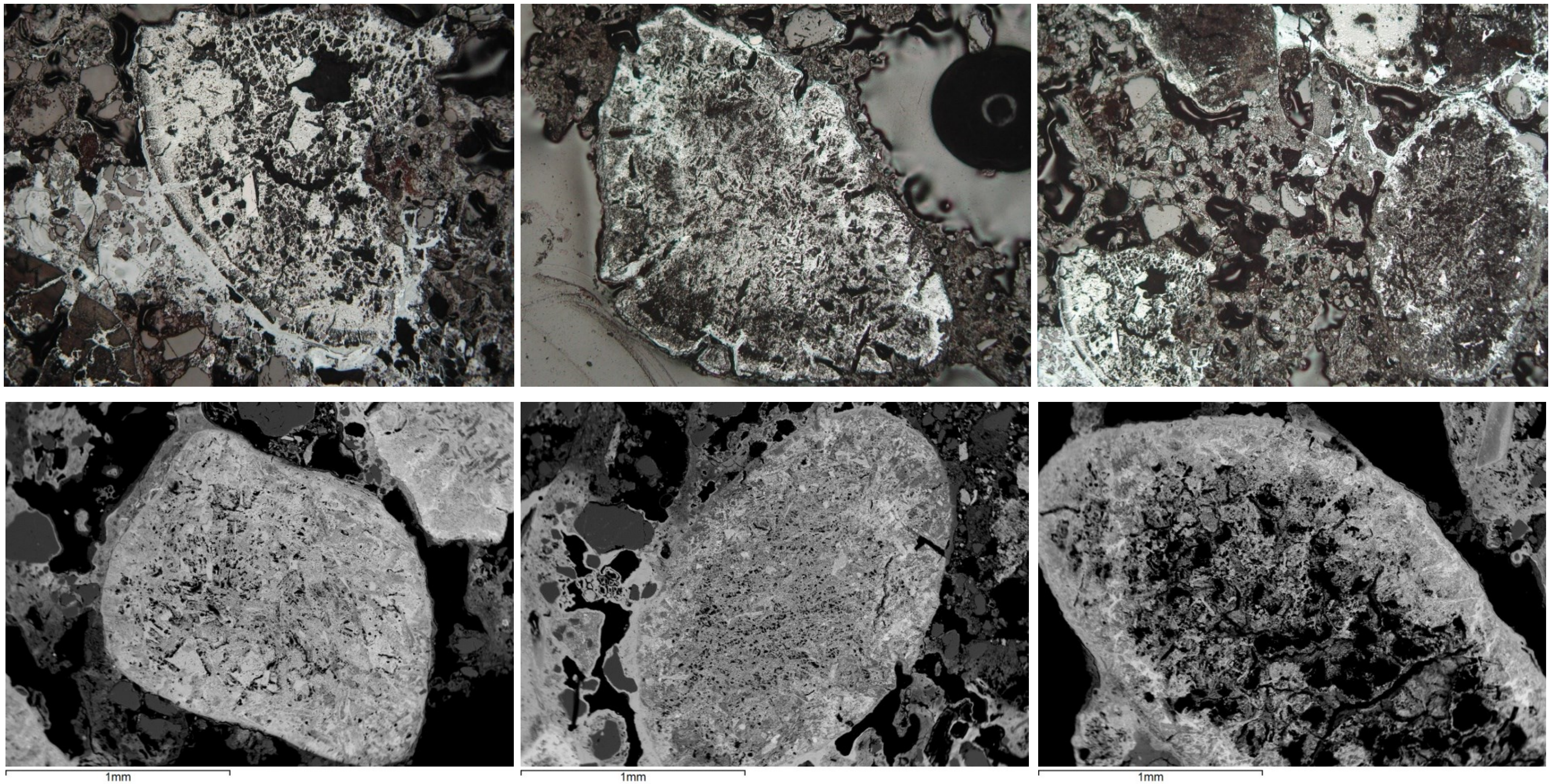


Figure 8.8 Micrographs and BSE images of pisoliths in KDTe002 bound by clay-like or quartz materials. Some pieces seem to be richer in iron oxides than others as suggested by a domination of white area.

(Image width for micrographs ≈ 3.5mm)

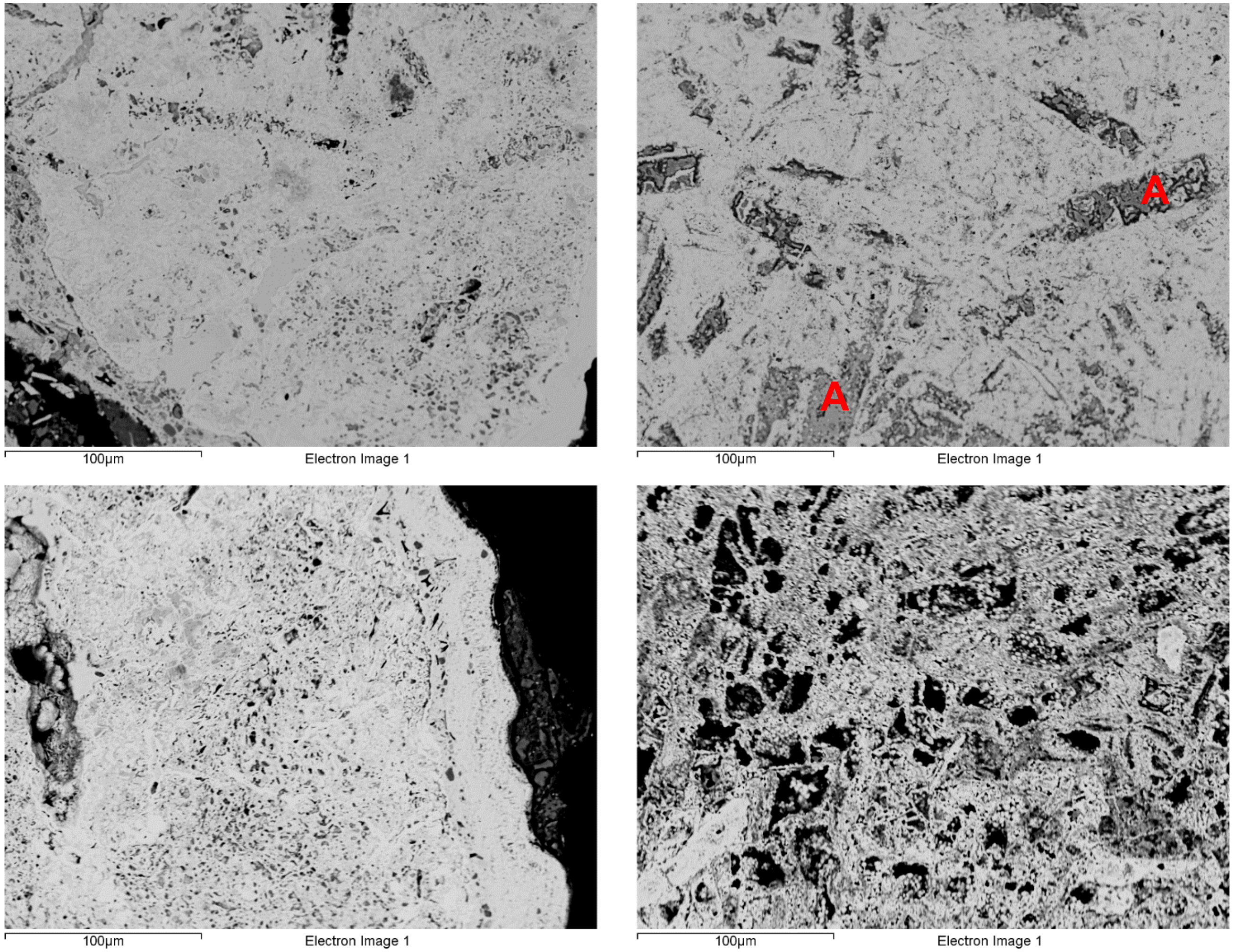


Figure 8.9 BSE images of the microstructures of pisoliths in KDTe002. This clearly identifies the dominant presence of iron oxides (white areas) and some interspersed rectangular phase (A). This phase (A) is characterised by three dominant oxides (Al_2O_3 (35-39 wt%), SiO_2 (34-40 wt%), and FeO (23-26 wt%)). Black areas are voids and resin.

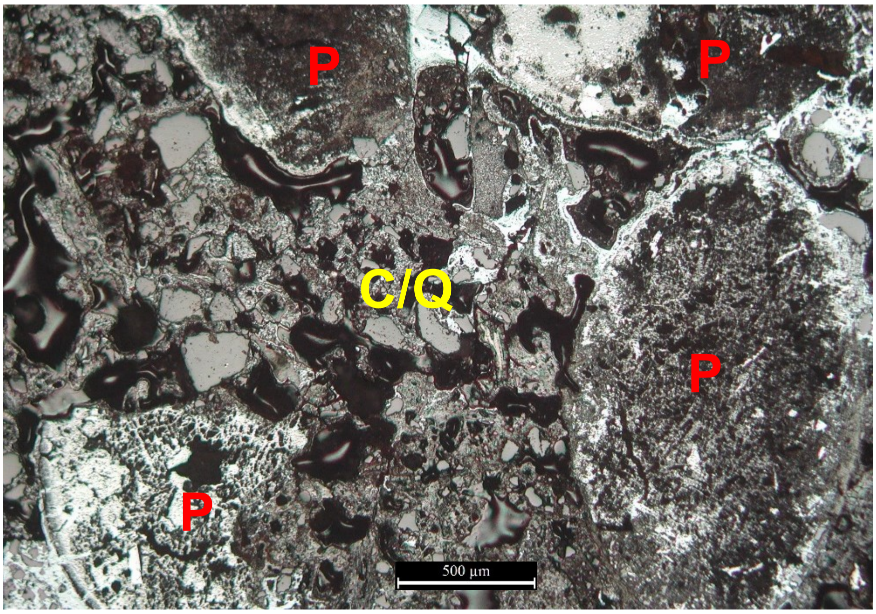


Figure 8.10 The micrograph shows a microstructural characteristic of the first laterite group. Pisoliths (P) are shown being surrounded by clay-like material and quartz particles (C/Q).

Pisoliths	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**TiO_2**	**FeO**
1	bdl	24.3	11.7	1.6	bdl	bdl	2.9	59.4
2	bdl	16.0	9.7	1.3	bdl	0.3	2.2	70.5
3	bdl	20.0	8.4	1.4	bdl	0.9	2.7	66.6
4	bdl	18.9	13.1	1.6	bdl	bdl	2.6	63.9
5	bdl	15.1	9.2	3.1	bdl	1.4	2.7	68.5
Mean	-	18.9	10.4	1.8	-	0.6	2.6	65.8
SD	-	3.7	1.9	0.8	-	0.5	0.3	4.3
CV	-	19	18	42	-	74	10	6
clay/ quartz part	0.7	14.9	44.2	1.4	0.4	0.3	0.8	36.9

Table 8.1 The chemical composition of some pisoliths in KDTe002 analysed by SEM-EDS. Values are expressed in wt% and normalised to 100%. Original analytical totals are expectedly low, around 75-89 wt% due to the presence of hydroxides and the porosity.

Mineralogical characterisation of the ore sample (KDTe001) using XRD provides information of the minerals in this specimen. The XRD pattern is consistent with iron oxyhydroxide ($Fe(OH)_2$) and quartz (SiO_2), thus in agreement with microstructural observations (Figure 8.11).

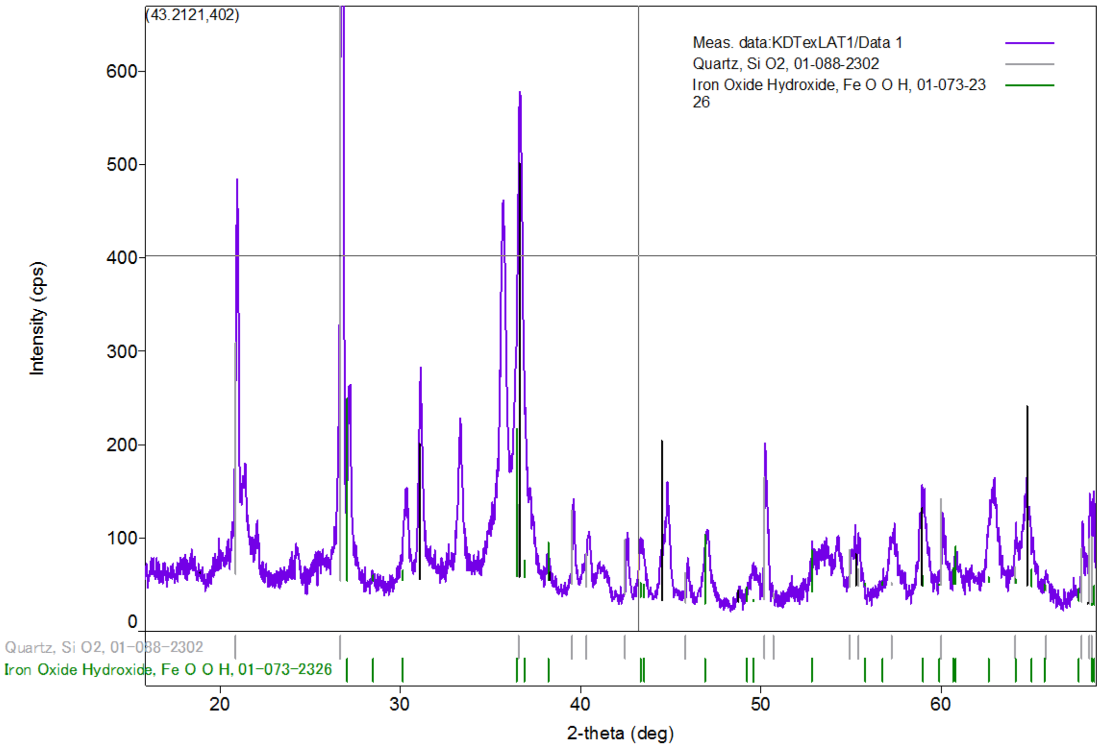


Figure 8.11 XRD spectrum of KDTe001 (purple). The measurement shows a pattern that corresponds to quartz (grey) and iron hydroxide (green).

The second group of archaeological laterite samples are from STH8. Unlike the previous group, all samples in this second group are nodular with a smooth reddish surface (Figure 8.12). Some samples can also be of amorphous shape (Figure 8.13). Their dark red or reddish colours are very similar to those of geological laterite and laterite blocks commonly seen at Khmer temples (Figure 7.98). Their cross-sections show a relatively homogeneous texture with small white inclusions dispersed across the body (Figure 8.14).

Figure 8.12 Laterite nodules from STH8 T1 (STH8e003, 006, 005)

Figure 8.13 One of amorphous laterite samples (STH8e006)

Figure 8.14 Profiles of the laterite samples (STH8e001, 004, 005)

Microstructural and chemical analysis, based on six samples, characterises these samples in more detail, from which three different areas can be described: quartz/clay-like material-rich area, quartz/iron oxide area, and iron oxide-rich area (Figure 8.15 and 8.17 and Table 8.2). The results of XRD analysis shows that the main iron-bearing mineral in the samples is goethite (α-FeO(OH)) (Figure 8.17 and 8.19). However, it has to be noted that the sizes of each area (and hence the iron richness) in each sample tend to vary, likely because of the natural heterogeneity of laterite.

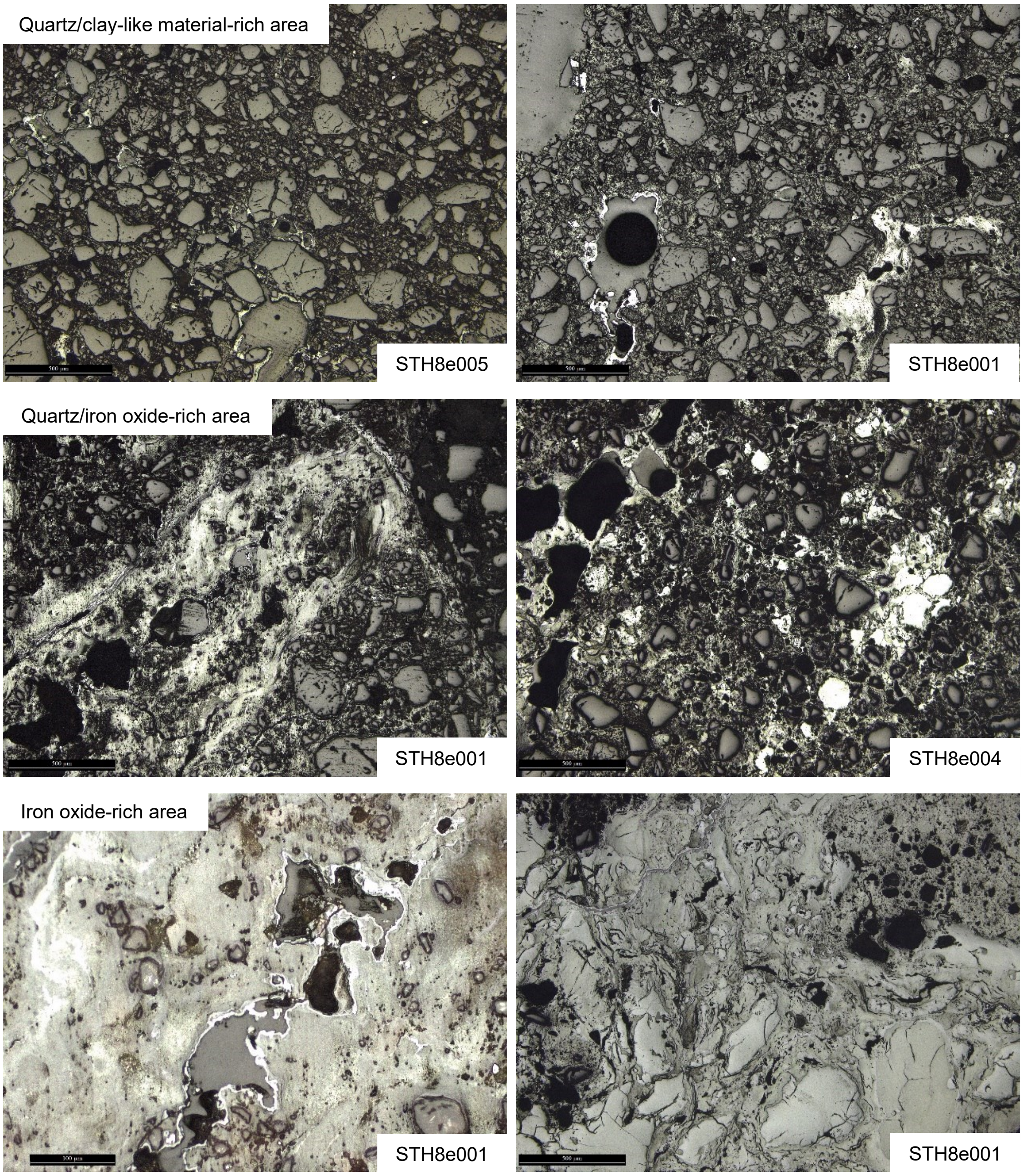


Figure 8.15 Micrographs of some laterite samples show the three main areas. The third area is where iron oxide (white region) concentrates most.

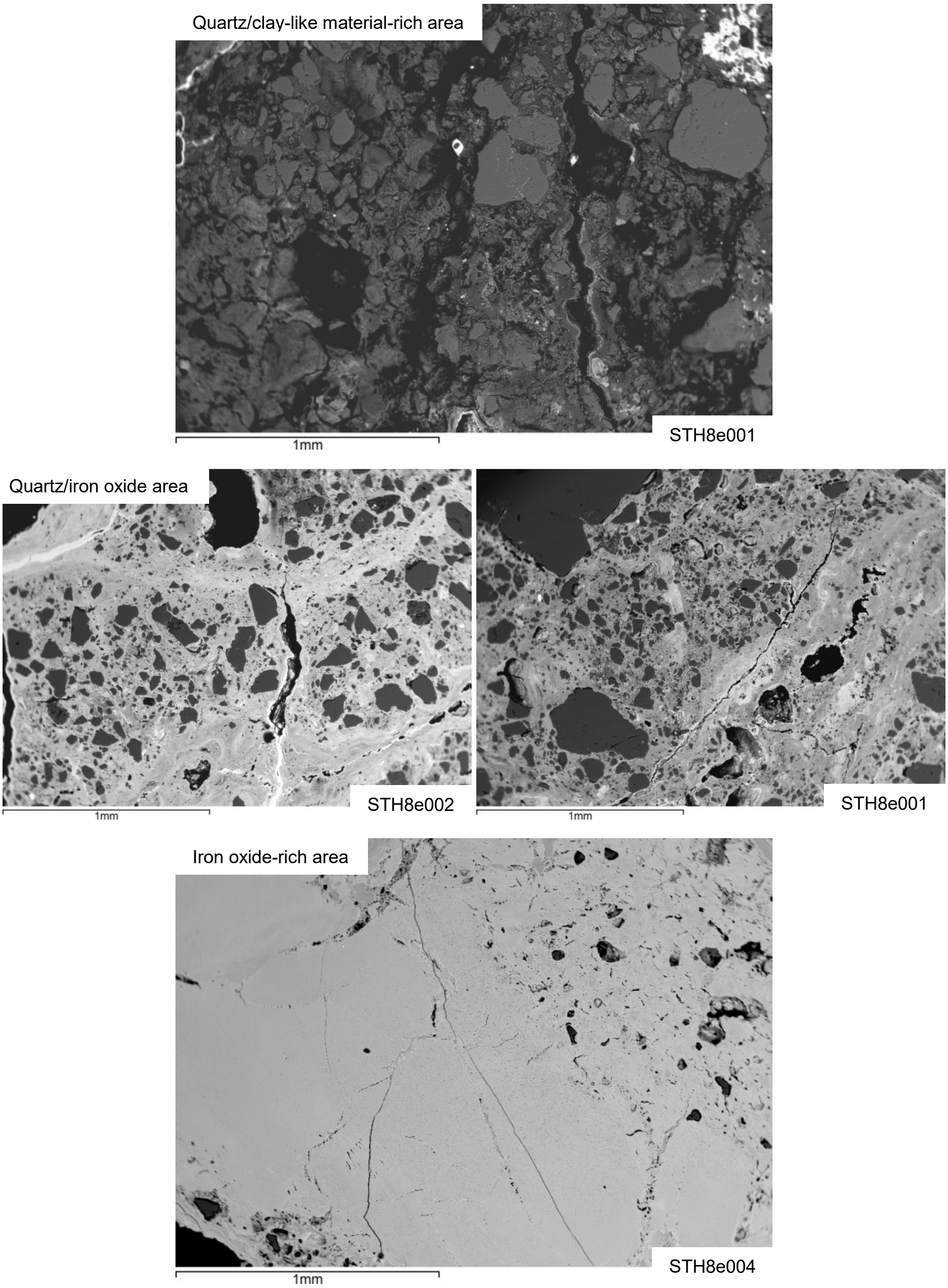
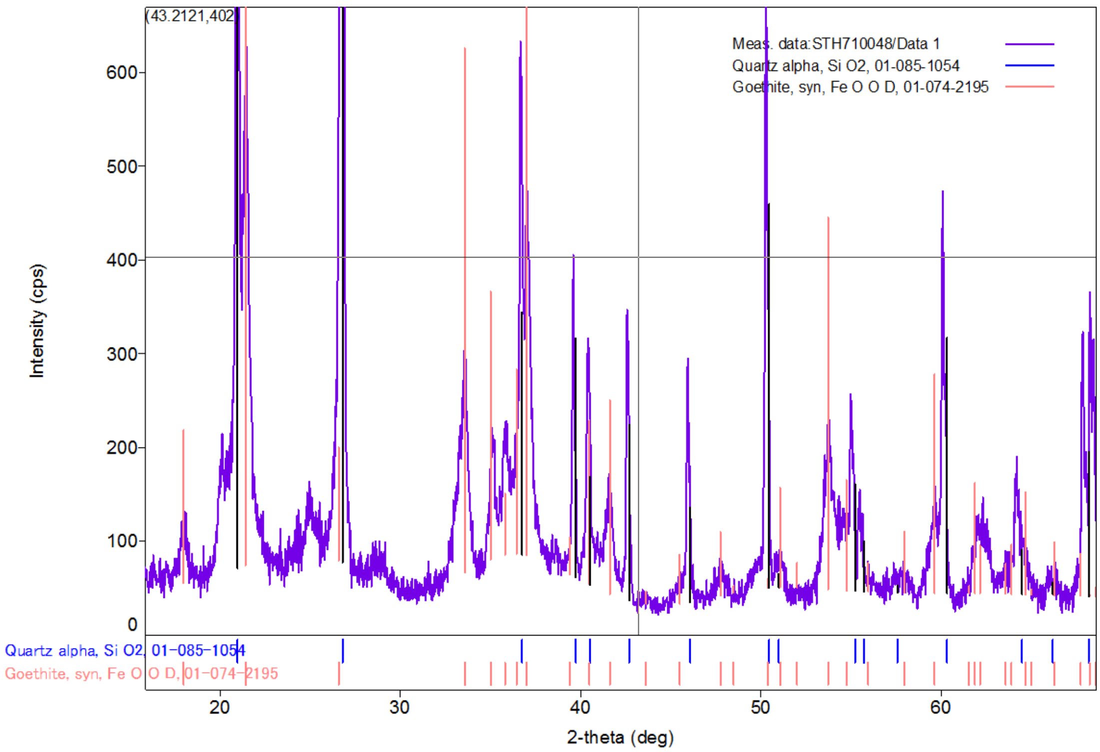


Figure 8.16 BSE images of the microstructures of some laterite samples in the second group show three main areas



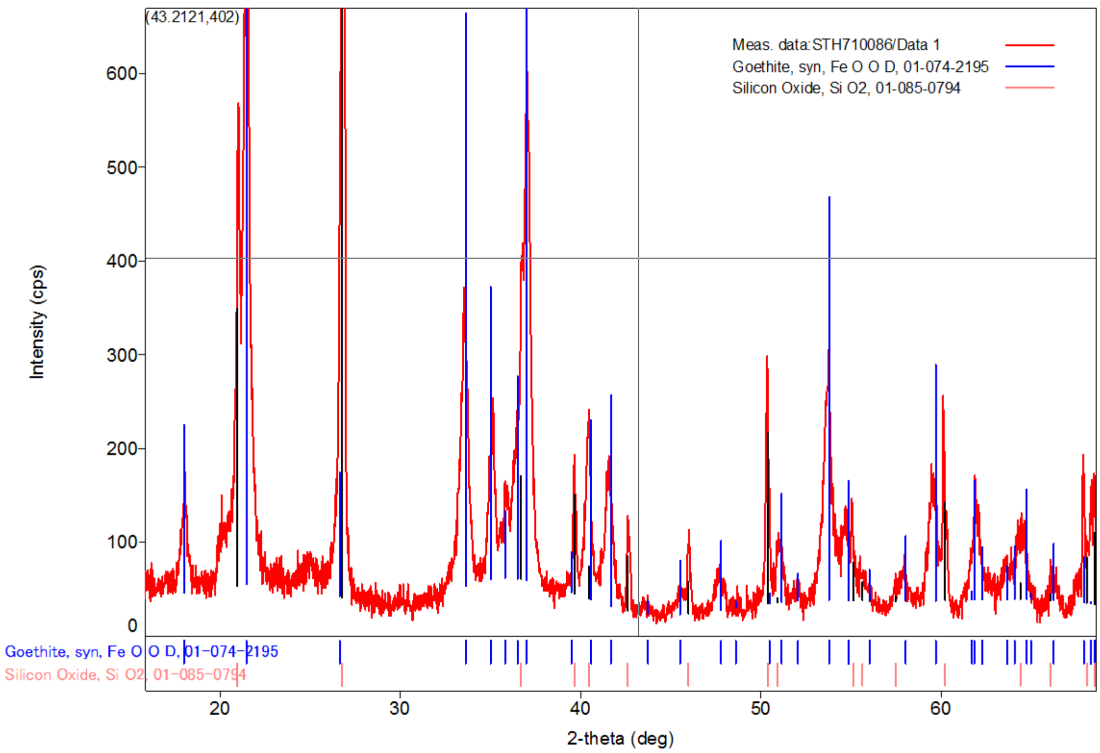


Figure 8.17 XRD spectrum of STH8e001 (top) and STH8e002 (below). The measurement shows a pattern that corresponds to quartz and geothite (iron oxyhydroxide).

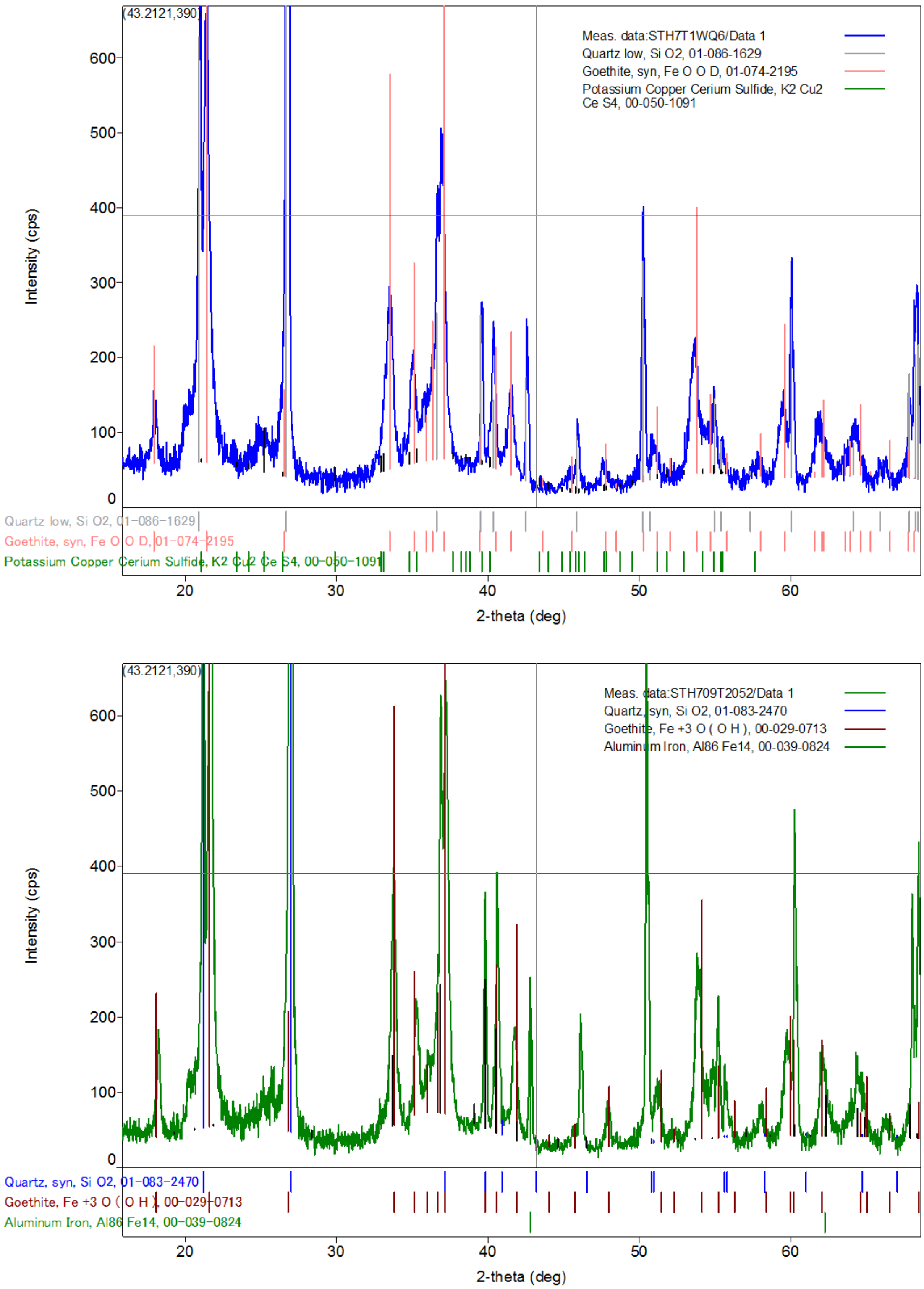


Figure 8.18 XRD spectrum of STH8e003 (top) and STH8e006 (below). The measurement shows a pattern that corresponds to quartz and geothite.

The third group comprises of the geological samples collected locally in order to compare with archaeological ones. The heterogeneous nature of laterite is clearly demonstrated by these samples as their structures and chemical compositions vary widely. Macrostructurally, despite their common reddish colour, they show also some internal areas that are orange/red (STH8-5LAT) or red/black (BPPLAT) (Figure 8.19 and 8.20) or of diverse colours (reddish to yellowish brown and reddish black) (BKTLAT) (Figure 8.21 and 8.22), rather than the relatively uniform texture seen in the second group. The heterogeneity of the geological laterite, contrasting with the relative homogeneity of the archaeological laterite described above, makes it likely that the archaeological samples underwent some kind of selection in the past, which will be discussed in the next section.

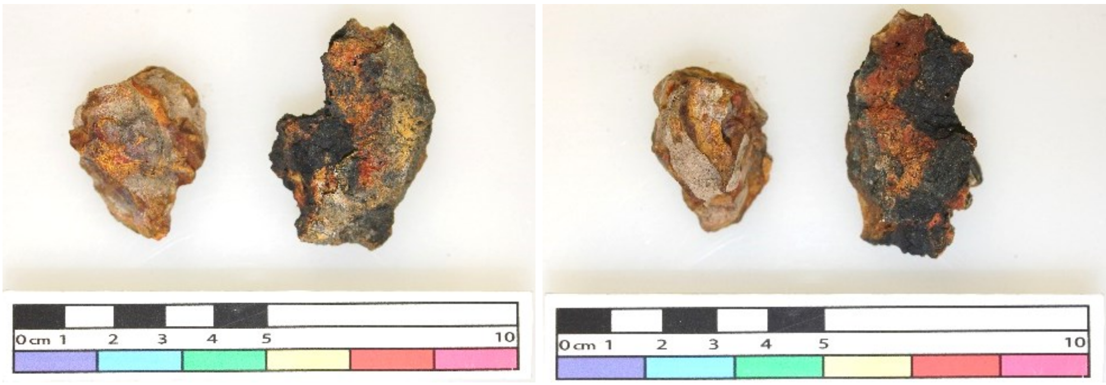


Figure 8.19 STH8-5LAT and BPPLAT before being cut

Figure 8.20 Cross-sections of STH8-5LAT and BPPLAT

Figure 8.21 BKTLAT

Figure 8.22 The cross-section of BKTLAT

Through microstructural and chemical analysis, three main areas are also identified in these samples (Figure 8.23). In BPPLAT, the black area was identified as containing MnO as high as 50 wt%, while STH8-5LAT contains quite comparatively high levels of TiO_2 (approximately 1.7 wt%) (Table 8.2). This chemical variation again emphasises a heterogeneous nature of laterite, even within the same area. Compared to the previous groups, the iron oxide-rich areas appear to be much smaller, while the first and second areas are larger.

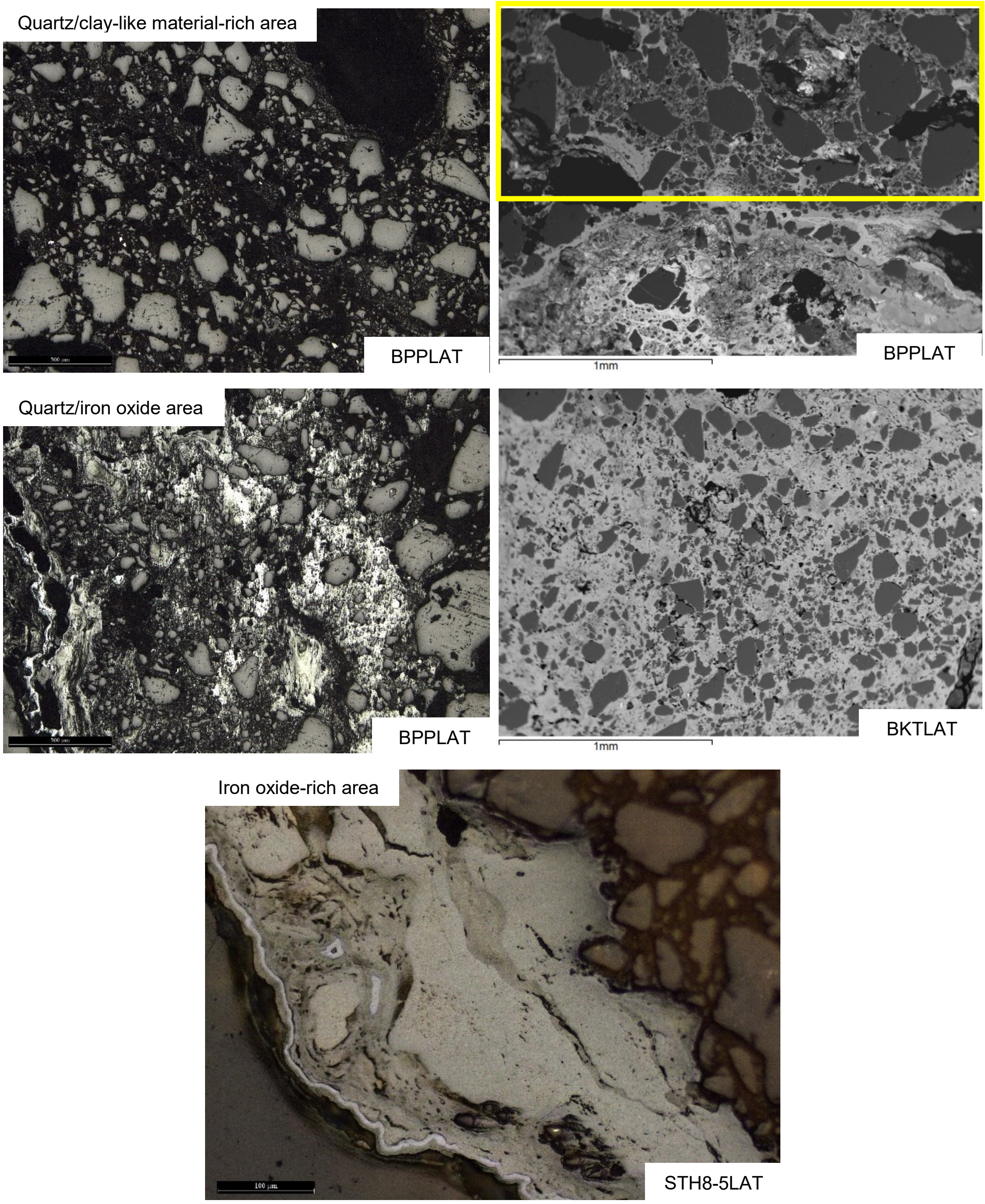


Figure 8.23 Three main areas found in laterite samples examined (micrographs (left columns) and BSE images (right columns))

		MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Analytical totals
Clay/quartz areas	KDT2e002	0.8	14.9	44.3	1.5	0.4	0.4	0.9	bdl	36.9	56.8
	STH8e001	bdl	28.7	64.9	0.2	0.3	bdl	1.9	bdl	3.9	54.9
	STH8e002										
	STH8e004										
	STH8e005	bdl	13.5	33.2	bdl	bdl	bdl	0.9	bdl	52.4	73.1
	STH8-5LAT	bdl	5.6	40.1	bdl	bdl	bdl	1.7	bdl	52.6	80.4
	BPPLAT	bdl	10.0	43.5	bdl	0.3	bdl	0.8	1	44.4	85.3
Clay-Fe areas	KDT2e002	bdl	4.4	18	bdl	bdl	0.5	bdl	bdl	74.6	77.1
	STH8e001										
	STH8e002	bdl	13.6	13.8	bdl	bdl	bdl	0.6	bdl	72.0	78.1
	STH8e004	bdl	8.3	8.8	bdl	bdl	bdl	2.8	bdl	80.0	78.8
	STH8e005										
	STH8-5LAT										
	BPPLAT										
Iron oxide-rich areas	KDT2e002	bdl	18.9	10.4	1.8	bdl	0.9	2.6	bdl	65.8	86.0
	STH8e001	bdl	19.6	20.4	0.7	bdl	bdl	0.6	bdl	58.8	80.3
	STH8e002	bdl	13.8	14.1	bdl	bdl	bdl	bdl	bdl	72.1	79.1
	STH8e004	bdl	8.4	9.7	bdl	bdl	bdl	bdl	bdl	81.9	78.5
	STH8e005	bdl	8.5	6.8	bdl	bdl	bdl	bdl	bdl	84.7	77.2
	STH8-5LAT	bdl	9.7	15.2	bdl	bdl	bdl	2.1	bdl	73.1	77.6
	BPPLAT	bdl	13.9	21.5	bdl	0.3	bdl	0.4	0.3	63.6	79.9

Table 8.2 Oxide concentrations for each distinguishable area in some laterite samples determined by SEM-EDS at 2000x magnification (250*250μm). The grey boxes mean that the mentioned areas could not be analysed at this magnification. The values for the iron oxide-rich regions of KDTe002 is an average of the analytical results of five pisoliths (see Table 8.1). Values are normalised to 100 wt%. The samples in bold letters are geological samples, while the rest are archaeological samples.

Bulk chemistries were determined by WD-XRF for 11 specimens covering the collections from three different contexts (Table 8.3 and 8.4). It should be noted that all samples, including the suspected ores from KDT2, were prepared in bulk without any attempt at 'beneficiating' them by separating the iron rich pisoliths.

Three main oxides, Al_2O_3, SiO_2, and FeO, dominates their chemistry in all cases. Two KDT2 samples are chemically comparable and contain the highest levels of Al_2O_3 and TiO_2 among all laterite samples studied. The samples from STH8 are more chemically variable for most oxides, including Al_2O_3, SiO_2, MnO, and FeO. Of all samples, STH8e001 is of interest as it contains higher MnO, BaO, and CeO_2. The chemistries of the geological samples are markedly variable as they come from different locations, thus different sources/formations. Some sources such as BPPLAT can contain considerable amounts of MnO, likely corresponding to the black areas shown in Figure 8.20. In terms of their richness in iron oxide, this varies considerably from 30-70 wt% FeO with an average of 58, 48, and 37wt% for each respective group mentioned previously.

wt%	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO
KDT2e001	14.77	23.21	0.96	0.11	0.15	1.35	0.16	0.08	0.18	58.91
KDT2e002	14.24	25.27	0.89	0.10	0.13	1.44	0.19	0.09	0.19	57.32
Mean	14.50	24.24	0.93	0.10	0.14	1.40	0.17	0.09	0.18	58.11
STH8e001	13.94	48.90	0.40	0.09	0.13	0.48	0.12	0.05	1.82	32.97
STH8e002	11.33	31.94	0.27	0.07	0.09	0.32	0.13	0.06	0.07	55.62
STH8e003	11.77	39.51	0.28	0.08	0.15	0.36	0.17	0.04	0.34	47.12
STH8e004	8.48	13.48	0.21	0.03	0.94	0.32	0.23	0.04	0.01	76.19
STH8e005	8.84	50.31	0.14	0.07	0.15	0.30	0.12	0.02	0.02	39.93
STH8e006	11.53	48.85	0.24	0.06	0.13	0.37	0.10	0.04	0.01	38.59
Mean	10.98	38.83	0.26	0.07	0.27	0.36	0.14	0.04	0.38	48.40
SD	2.0	14.3	0.1	0.0	0.3	0.1	0.0	0.0	0.7	15.7
CV	19	37	34	31	125	18	31	34	190	32
STH8-6LAT	11.50	48.54	0.05	0.10	0.04	0.63	0.15	0.11	0.21	38.46
BPPLAT	8.07	58.24	0.03	0.23	0.05	0.38	0.06	0.05	2.76	29.31
BKTLAT	12.41	41.48	0.07	0.09	0.08	0.44	0.23	0.05	0.21	44.78
Mean	10.66	49.42	0.05	0.14	0.06	0.49	0.14	0.07	1.06	37.52
SD	2.3	8.4	0.0	0.1	0.0	0.1	0.1	0.0	1.5	7.8
CV	21	17	39	56	37	27	59	43	138	21

Table 8.3 Selected major and minor oxide concentrations of the laterite samples analysed by WD-XRF. Values are normalised to 100%. (see Appendix H for the full analytical results)

ppm	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3
KDT2e001	17	522	19	19	391	254	bdl	74	bdl
KDT2e002	14	391	18	9	391	250	16	257	28
Mean	16	457	19	14	391	252	-	166	-
STH8e001	116	58	16	18	730	4699	bdl	5219	bdl
STH8e002	272	123	13	6	339	78	5	150	40
STH8e003	310	72	17	11	512	724	bdl	188	bdl
STH8e004	52	23	bdl	33	309	89	25	71	75
STH8e005	42	36	23	19	789	103	bdl	bdl	bdl
STH8e006	115	47	15	6	525	160	24	bdl	bdl
Mean	151	60	17	15	534	975	-	961	-
SD	113.3	35.5	3.9	10.1	196.2	1840.9	-	2086.2	-
CV	75	59	24	66	37	189	-	217	-
STH8-6LAT	295	25	14	4	692	629	9	502	8
BPPLAT	144	60	29	42	538	6569	34	617	31
BKTLAT	119	23	12	8	566	644	34	51	bdl
Mean	186	36	18	18	599	2614	26	390	16
SD	95.1	20.8	9.5	21.3	82.1	3425.1	14.2	299.2	13.1
CV	51	58	53	118	14	131	55	77	82

Table 8.4 Selected trace oxide concentrations of the laterite samples analysed by WD-XRF. Values are normalised to 100%.
(see Appendix H for the full analytical result)

8.3.1.2 Discussion and summary

The laterite samples comprise mainly of oxyhydroxide iron minerals (particularly goethite), clay minerals, and quartz which are all common components found in laterite (see section 4.3.3.1 and Uchida *et al*. 1999, 163). Microstructurally, iron oxide-rich areas can concentrate in specific areas, but overall they seem to disperse across the bodies of the samples, with the exception of the KDT2 samples, where the oxide concentrates as pisoliths. Since the Ban Kruat samples were not X-radiographed, it is unclear if their structure is comparable to the laterites from Ban Dong Phlong, which display concentric rings of iron oxide enveloping quartz/clay-like core (Figure 4.15). Chemically, irrespective of their context, their dominant chemical components consist of Al_2O_3, SiO_2, and FeO. High alumina levels are characteristic of these laterite samples, as reported in studies in Thailand and Cambodia (8-22 wt%) (Nitta 1996, 1997; Uchida *et al*. 1999, 169; Watsantachad 2005, 124) and in Tanzania (Lyaya *et al*. 2012). The microanalysis clearly shows that the high alumina is prevalent in both the clay- and iron oxide-rich parts. Concentration of other oxides (e.g. TiO_2 and MnO) tends to vary between samples, especially those from STH8. Thus, under microanalysis, laterite samples reveal heterogeneous nature despite their similar macroscopic appearance.

High alumina is mostly characteristic of the iron oxyhydroxide group (e.g. limonite, goethite, and lepidocrocite (γ-FeO(OH))) due to a concentration of leached elements, including aluminium, during their formation (see section 4.3.3.1). In laterite iron ore deposits containing iron oxyhydroxide minerals, Al_2O_3 levels can reach up to 20% (Pohl 2011, 154); although they may vary significantly from deposit to deposit. This is in contrast to haematite and magnetite, which typically contain less than 6-8 wt% alumina. It is known that alumina is one of the main oxides affecting viscosity of slag, whereby higher alumina in $FeO-SiO_2-Al_2O_3$ systems tends to increase the melting point and hence the viscosity at a given temperature (Bachmann 1982, 13; Bodsworth and Bell 1972, 163; Chen *et al*. 2013). Consequently, in order to tap high-alumina slag, adjustments are needed in terms of operational temperatures or ratios of charge components to ensure more fluid slag.

Since Ban Kruat slag is very rich in alumina (12-15 wt%, see section 8.3.3.1.1.2), determining the main source of this oxide is critical to clarify if laterite ore was used. It is known that not only laterite but also technical ceramics (Table 8.6) contain considerable quantities of alumina, and both can contribute this oxide to slag formation (Pleiner 2000, 252; Senn *et al*. 2009). Mass balance calculations and a chemical comparison (e.g. ratios between SiO_2 and Al_2O_3) between all smelting components presented in section 8.4.1.1.2 will address this question.

In terms of iron oxide content, irrespective of their shapes, most samples contain relatively low quantities of FeO (less than 60 wt%). Only STH8e004 stands out with the highest FeO levels of 75 wt%. Low FeO levels are expected for this kind of ore, which is considered low grade (see section 4.3.3.1). Interestingly, with such low iron values, they cannot be easily modelled to produce “typical” bloomery iron slag (about 50-70% FeO, about 20% SiO_2, and other oxides (Al_2O_3, CaO, TiO_2, and MnO)) (Bachmann 1982, 30; Craddock 1995, 235; Pleiner 2000, 252; Rostoker and Bronson 1990, 92), or indeed the somewhat more atypical Ban Kruat slag (see section 8.3.3.1). It is assumed by most mass balance models that the iron content in the ore has to be higher than that in the slag as each ore unit will only free up iron to make the bloom once it has sacrificed the FeO needed to make one unit of slag. Therefore, ore with higher iron oxide than in iron slag is required (see section 4.2). Again, the calculation might clarify this issue.

Another interesting issue emerging from the laterite analyses is the possibility that specific laterite types were selected in Ban Kruat. The evidence from STH8 appears to point more strongly to this direction than that from KDT2, although none is conclusive. The laterite found at STH8 is consistently nodular in morphology, possibly indicating that local smelters exploited these formations preferentially from local deposits (see section 7.2.7.1). However, the chemical analyses show that iron contents vary significantly from piece to piece. Thus, if nodular laterite was sorted for smelting, it is not clear if local smelters had particular techniques to recognise iron-rich nodules from poor ones. To what extent these were beneficiated is still questionable. Due to their hardened clay-like structure, crushing might turn them into powder and still not lead to a higher concentration of iron oxide, in contrast to the beneficiation of haematite or magnetite (see also Kasungu case (Gordon and Killick 1993, 267)). Moreover, as demonstrated above, the distribution of iron-rich zones internally would make it presumably difficult to judge their richness by visual examination. At the same time, the peanut size of these nodules may have rendered them suitable to be used directly. Therefore, it is possible that they were charged into the furnace as nodular grains if deemed acceptable for smelting.

For KDT2, like for STH8, pieces of laterite may have also not been treated; even though the highest concentration of iron oxide is found in small pisoliths of less than 1 cm in size, it is likely that crushing would again only transform them into dust or particles too small to be charged into furnace.

Whatever the case, the rare residual mineral inclusions found in two slag samples, and thought to be fragments of laterite, differently suggest that the smelting at KDT2 and STH8 exploited both types of laterite rather than favouring a single type (Figure 8.61).

One benefit of charging untreated laterite may be the introduction of additional silica, which is already available as quartz particles seen in microstructure, into the smelting system in order to promote the formation of fayalitic slag (see section 4.2 for the formation of iron slag).

All the issues discussed above will be used to model the smelting mechanisms and offer a technological reconstruction of Ban Kruat iron smelting, as discussed in later sections.

8.3.2 Technical ceramics

To understand the role of technical ceramics in the smelting system, some samples of tuyères, clay plugs, and furnace fragments were examined structurally and chemically. Local clays and domestic pottery were also compared chemically to the technical ceramics in order to assess their relationships.

The samples examined fall in three groups. The first group concerned raw clays collected from three different locations in Ban Kruat: KDTTS, sampled from a stream bank of Huai Ta Sek near KDT2, KDTRF, sampled from a rice farm near KDT2 (see Figure 7.14 and 7.33), and STH8TK, sampled from a stream bank of Huai Tako. The second group comprised of technical ceramics associated with the slag deposits visited. The KDT2 samples, which were closely associated with smelting evidence, were the main focus for they were the bulk of technical ceramics examined in Chapter 7. The resultant data would be assessed with the slag and laterite samples collected at the same site. Additional samples from other deposits (KY5, KDT1 and 3, STH8 M1 and M2, STH8/2 M6, STH10 S) were also included. The last group consisted of fragments of reduced wares from KDT2 (Figure 7.56) and locally produced Khmer brown glazed stoneware (see section 6.3.3).

8.3.2.1 Further characterisation and discussion

From a macroscopic examination in section 7.3.2.2, some similar features have been observed. Many of the samples examined, including tuyères, cores of clay plugs, and furnace fragments, were often found without the original external surface. However, there is an exception for tuyère nozzles and the front part of clay plugs where vitrification holds the structure together – even though this may have been thermally eroded. The examination of some broken pieces suggested that similar clay pastes, tempered with organic matter, may have been used for the production. Moreover, these pastes appear to have been refractory enough to survive high-temperature operation despite their friable internal structure.

Cross-sections and micrographs of the KDT2 samples (Figure 8.24-8.27) complement the findings summarised above. In addition to elongated voids left by burnt-out organic matter (Figure 7.94), small quartz grains and large rock inclusions, probably laterite fragments, are shown to be embedded in clay matrices. Based on macro- and microscopic evidence, the clay paste used for producing these ceramics was raw clay tempered with organic matter and quartz grains (sand?). Occasional laterite fragments, seen as large inclusions (Figure 8.26), might have been included in the paste, but this point could not be ascertained because of the structural similarity between laterite (see section 8.3.1.1) and the clay materials. Nonetheless, the presence of laterite fragments is not surprising since laterite deposits are part of local geology (see section 6.2). Further analysis such as petrographic analysis may help clarify to what extent laterite fragments were deliberately added as temper or residual in clays.

Colour gradients were also identified in these cross-sections, ranging from a greyish white side presumably exposed to higher temperature and reducing atmospheres, to an orange-red side at the other end. This pattern exhibits clearly in tuyère and furnace fragments (Figure 8.24 and 8.27).

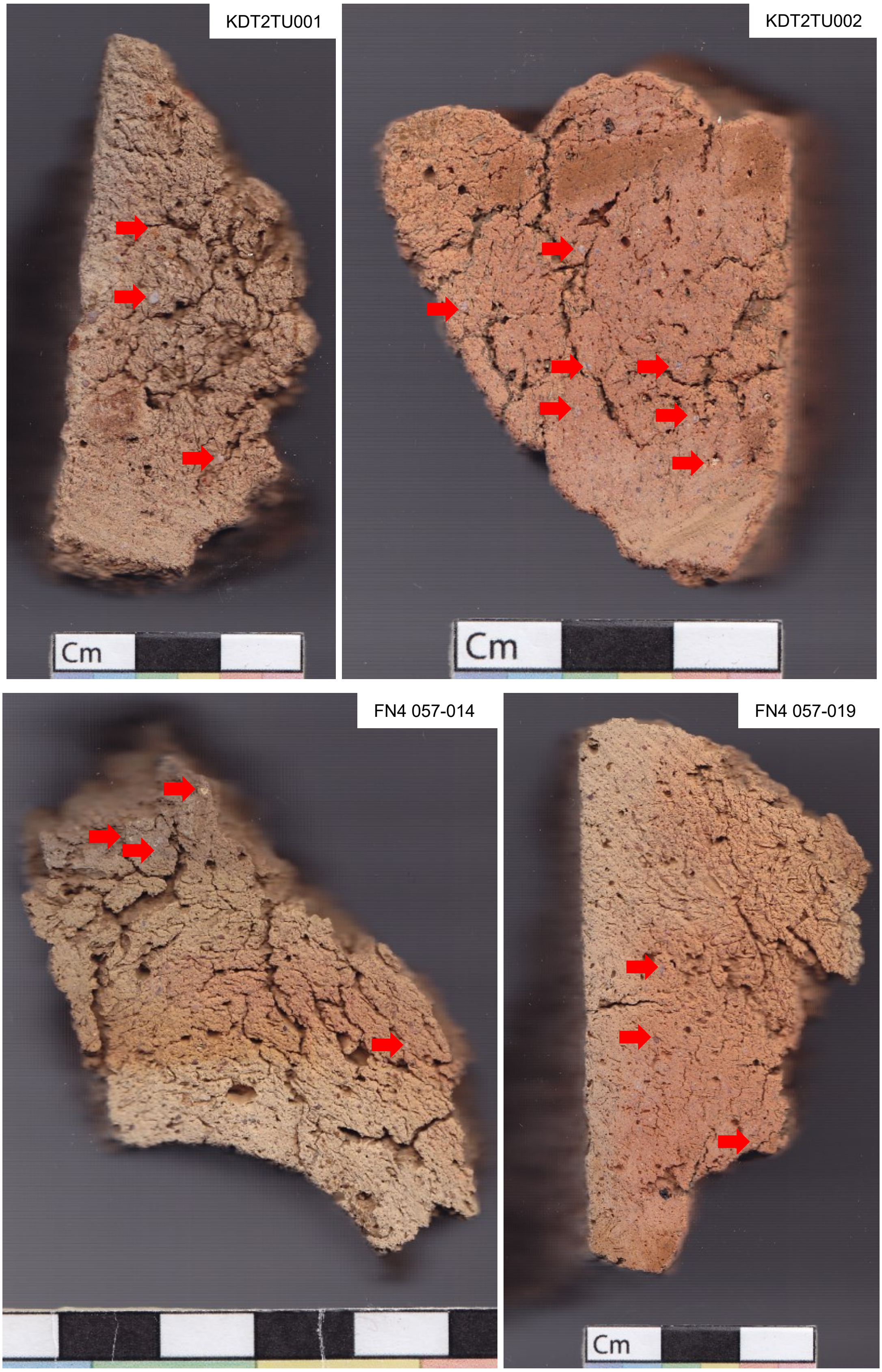


Figure 8.24 Cross-sections of some tuyère fragments. Cracks can be observed in all samples shown. Small white inclusions are seen in some samples indicated by red arrows.

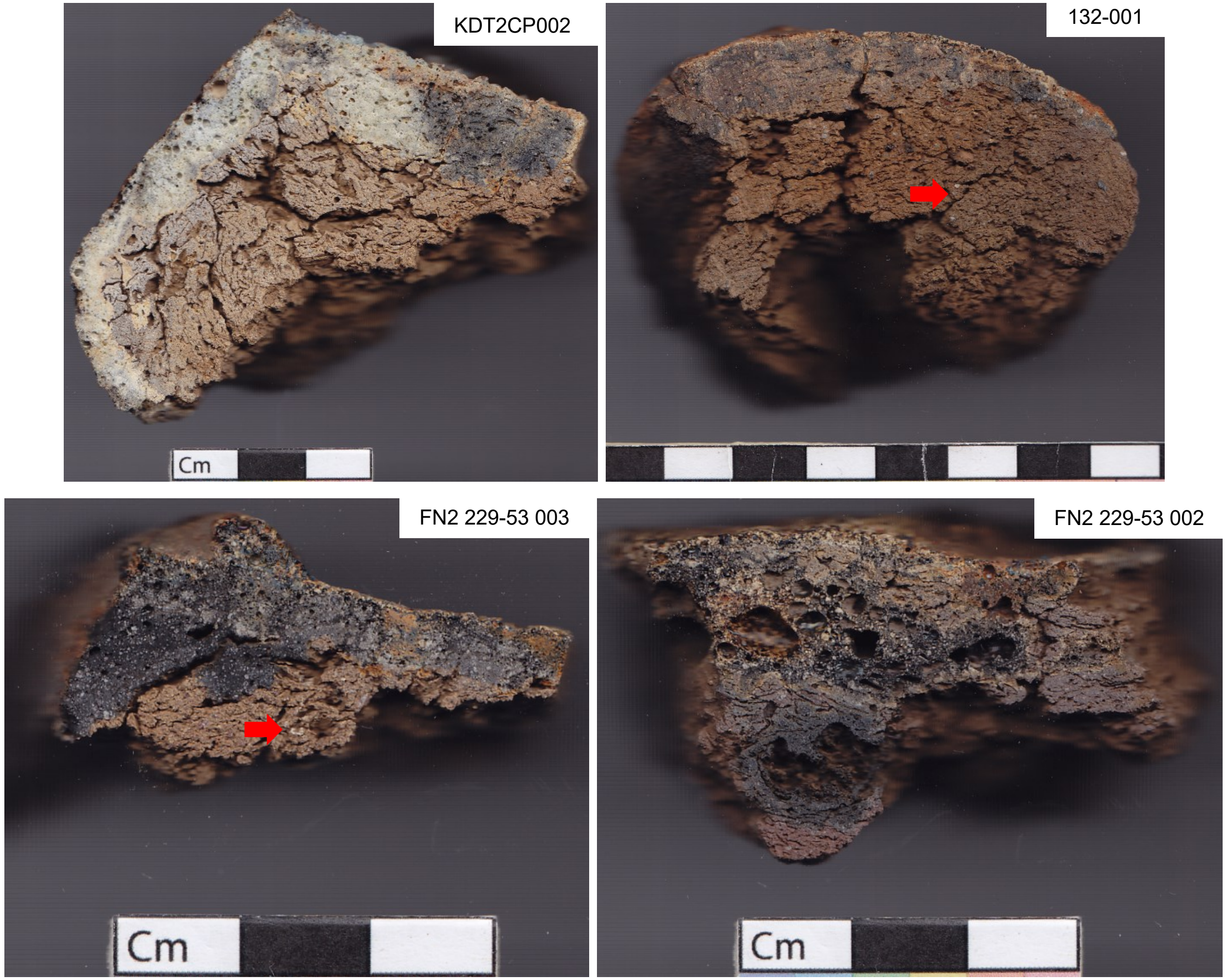


Figure 8.25 Cross-sections of some clay plug fragments. Only front vitrified parts with ceramic parts attached are shown here. Inclusions in the ceramic parts are indicated by red arrows.

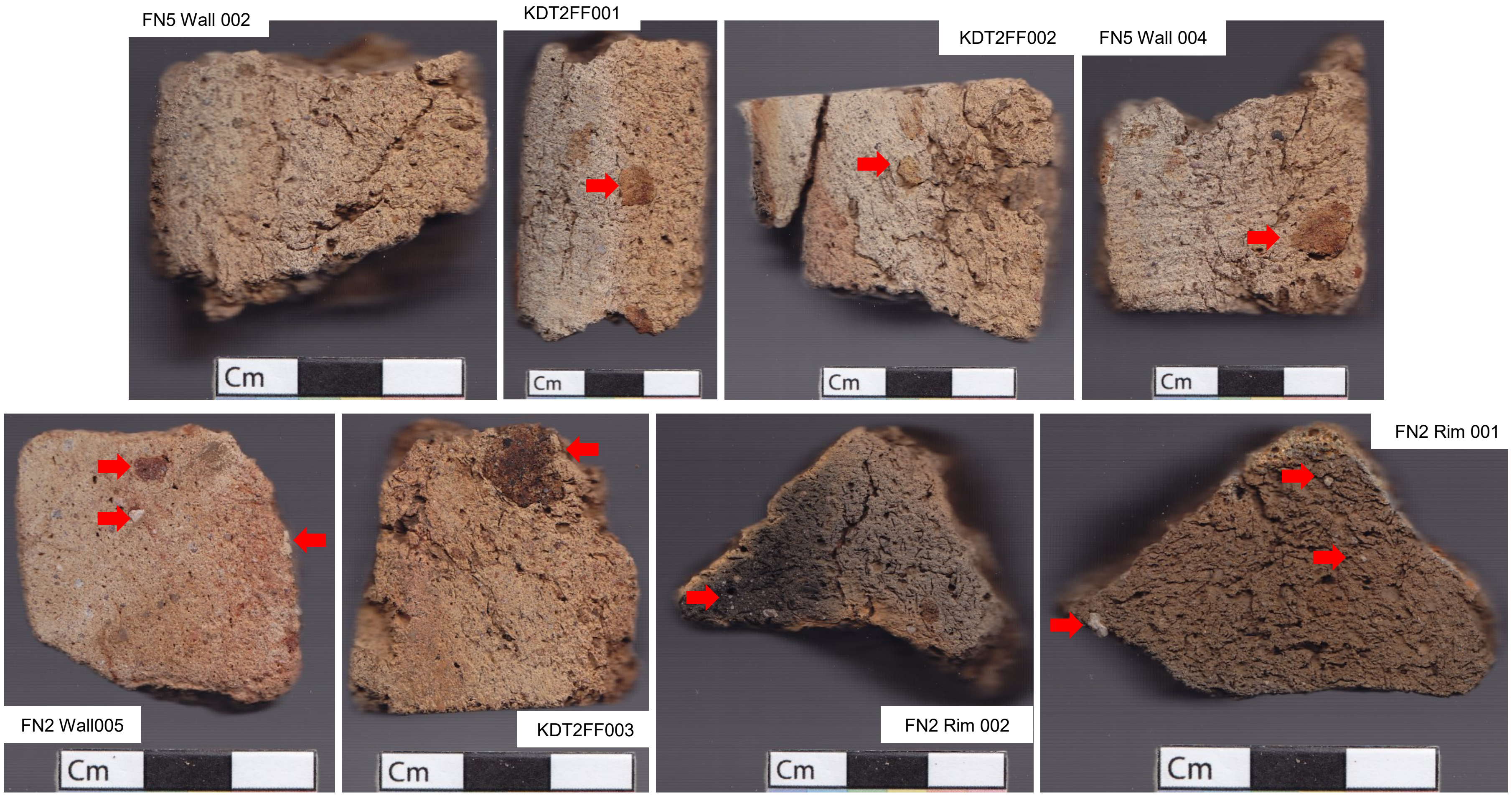


Figure 8.26 Cross-sections of furnace fragments. Inclusions are indicated by red arrows.

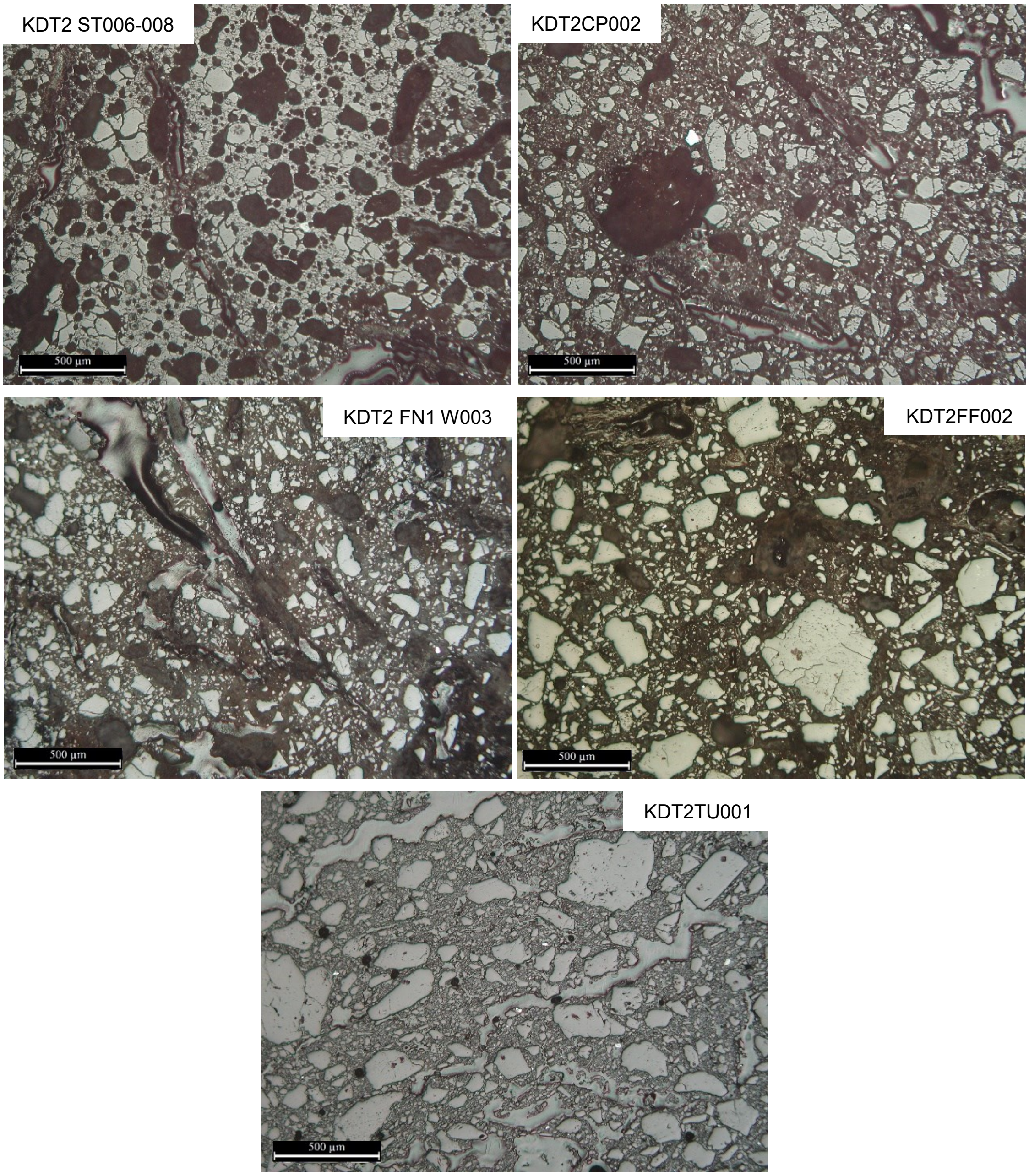


Figure 8.27 Micrographs show the microstructure of some KDT2 clay plugs (top), furnace fragments (middle), and tuyère (below). Abundant quartz particles dominate clay matrices, while elongated voids (organic matter) can also be seen.

The quartz particles are of various shapes and sizes, ranging from less than 100μm to 500μm (Figure 8.27). This suggests that the clay and quartz temper used were not sieved to sort particles. Quartz particles take up much more volume than the clay itself, which may explain the friable structure of the technical ceramics examined. It seems that, as clay was so heavily tempered by quartz, it increased its porosity and lost its plasticity to firmly hold its shapes. Most technical ceramics found were in small sizes and rarely in complete conditions. Cracks observed possibly reflect the little clay binder. Despite their poor structure, it is apparent that they could maintain their integrity and survive at least one smelt, but would crumble during post-smelting and depositional periods. An exception is the vitrified parts (e.g. front part of clay plugs and tuyère nozzles) where vitrification helps retain their shapes; however, these likely broke off the larger ceramic during the post-depositional period.

Although this clay paste recipe resulted in poorly plasticity, it contributed to improve the refractoriness of the material. Quartz particles can remain inert and are less likely to melt and react in relatively high-temperature operations since quartz melts at 1,600-1,700°C, which is much higher than any ancient high-temperature process. However, it should be noted that quartz can react with iron oxide to form fayalite at the temperature of 1,200°C; therefore, it is very likely that in iron smelting parts of the material can be melted and become vitrified due to the reaction with iron oxide in the system.

The refractory character of the ceramics also stems from the relatively high Al_2O_3 and low FeO nature of the clay, determined by SEM-EDS (Table 8.5). The use of this kind of clays can increase refractoriness of the resulting ceramics high-temperature activities (Freestone 1986; Freestone and Tite 1989). This clay when fired may also give a lighter colour reflecting the clay chemistry (Freestone 1986, 159). Neverthess, based on their chemistry, the clay analysed is not highly refractory by modern standards (typically containing at least 30 wt% Al_2O_3).

A refiring test of technical ceramic samples following a protocol established in Chapter 5, strengthens this impression. The experiment indicated that they could survive temperatures of 1,300°C without vitrification or new cracks (Figure 8.28). It should be noted, however, that this refiring test did not replicate the conditions created during the smelting operation, where fluxing agents (e.g. iron oxide) and reducing atmospheres might promote vitrification at lower temperatures.

Figure 8.28 Refired KDT2 furnace fragments, compared to the same samples before being refired in Figure 8.26. No clear vitrification can be observed after being fired at 1,300°C for two hours.

wt%	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	FeO
KDTCP001	0.4	20.4	67.3	1.3	0.7	1.2	8.6
KDT2FF003	0.4	15.6	78.0	bdl	0.3	0.8	5.0
KDT2 FN5B001	0.3	13.8	80.3	0.3	0.4	1.1	3.8
KDT2 FN5B002	0.4	24.2	68.5	0.5	0.3	1.1	5.0
KDT2 FN5B003	0.5	13.0	81.8	0.7	0.4	1.0	2.7

Table 8.5 Mean SEM-EDS chemical data of the matrix areas of some technical ceramics from KDT2, normalised to 100%. The chemical analysis of the ceramic matrices targeted areas free from inclusions, typically smaller than 250*250µm; however, inevitably, some mineral inclusions may have been analysed.

The structural characterisation on the KDT2 samples was supplemented by bulk chemical analyses of these and other ceramics to assess their similarities (Table 8.6 and 8.7). The results obtained agree with previous examinations by SEM-EDS and allow us to expand our characterisation to other sites. Almost all technical ceramic samples analysed are non-calcareous and very rich in SiO_2 (approximately 77-90 wt%) due to the abundant quartz inclusions. Al_2O_3 content is fairly high for all samples though varying from 6-17 wt% with an average of approximately 10-13 wt%. As shown in the SEM-EDS analyses presented above, the actual Al2O3 content in the ceramic matrices is likely higher, but appears diluted in these bulk analyses by the quartz temper. SiO_2:Al_2O_3 ratios range from approximately 1:5 to 1:13 with an average around 1:7. The low levels of FeO (below 4 wt%) and potentially fluxing alkali oxides would render the ceramics more resistant to high temperatures. Nevertheless, they still met the original requirement to survive in high-temperature smelting operations.

Wt%		Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO
local raw clay	KDTTS	8.80	88.03	0.05	0.34	0.10	0.63	0.01	0.01	0.03	1.81
	KDTRF	5.47	91.04	0.01	0.12	1.73	0.36	0.00	0.03	0.09	0.97
	STH8TK	11.42	85.30	0.07	0.23	0.11	0.64	0.01	0.01	0.04	2.01
Technical ceramics	KDT2CP001	12.23	83.64	0.06	0.14	0.23	0.57	0.02	0.02	0.14	2.80
	KDT2CP002	10.22	86.59	0.07	0.10	0.16	0.49	0.02	0.04	0.07	2.12
	KDT2FF001	11.47	84.93	0.10	0.11	0.39	0.49	0.01	0.05	0.06	2.22
	KDT2FF002	12.15	84.19	0.07	0.12	0.44	0.48	0.02	0.04	0.06	2.26
	KDT2FF003	13.99	80.45	0.29	0.32	0.41	0.64	0.02	0.02	0.24	3.45
	KDT2TU001	10.72	83.94	0.12	0.16	0.26	0.41	0.01	0.02	0.42	3.73
	KDT2TU002	11.20	85.32	0.09	0.16	0.42	0.64	0.01	0.02	0.02	1.94
	Mean	10.77	85.34	0.09	0.18	0.43	0.53	0.01	0.03	0.12	2.33
	SD	2.3	2.8	0.1	0.1	0.5	0.1	0.0	0.0	0.1	0.8
	CV	21	3	81	48	112	19	31	53	105	35
	STH8T1TU	15.61	80.70	0.48	0.26	0.38	0.57	0.01	0.02	0.00	1.81
	STH8T1CP	14.61	80.76	0.11	0.10	0.17	0.58	0.02	0.02	0.02	3.48
	STH8T1FF	12.01	85.54	0.19	0.15	0.24	0.43	0.01	0.01	0.01	1.26
	STH8M1CP	12.99	84.27	0.08	0.07	0.10	0.50	0.01	0.02	0.02	1.81
	STH8M1FF	14.28	82.97	0.13	0.25	0.19	0.55	0.01	0.02	0.00	1.46
	Mean	13.78	81.97	0.57	0.24	0.43	0.52	0.01	0.02	0.02	2.28
	SD	1.6	2.4	0.6	0.2	0.3	0.1	0.0	0.0	0.0	1.0
	CV	12	3	112	66	80	14	31	23	102	42
	STH8T1H	12.87	80.89	1.49	0.46	0.92	0.50	0.02	0.02	0.05	2.59
	KY5TC	11.94	84.30	0.05	0.20	0.15	0.49	0.01	0.02	0.08	2.68
	KDT1FF	6.76	91.11	0.11	0.06	0.29	0.33	0.00	0.02	0.01	1.22
	KDT3TU	10.38	86.26	0.47	0.23	0.29	0.50	0.01	0.01	0.02	1.74
	KDT3CP	7.96	89.47	0.04	0.03	0.11	0.36	0.01	0.01	0.04	1.83
	STH8/2TC	17.86	77.30	0.14	0.47	0.48	0.57	0.01	0.02	0.17	2.80
	STH10CP	9.03	88.20	0.05	0.08	0.11	0.56	0.01	0.01	0.10	1.72
Domestic pottery	KDT2DP001	16.93	66.61	0.59	1.42	2.40	2.91	0.04	0.02	0.14	8.65
	KDT2DP002	24.83	64.23	0.23	2.88	0.89	0.54	0.02	0.01	0.04	6.06
	KDT2DP003	21.58	65.83	3.22	2.78	0.77	0.50	0.02	0.01	0.04	4.90
	KDT2DP004	19.02	64.61	5.32	2.02	1.05	0.63	0.02	0.02	0.06	6.74
	KYKi	20.79	68.48	0.02	3.11	0.12	0.61	0.02	0.01	0.04	6.63
	NC4Kh	17.46	73.57	0.04	1.75	0.16	0.61	0.02	0.01	0.03	6.21

Table 8.6 Selected major and minor oxide concentrations of selected ceramic related samples determined by WD-XRF and normalised to 100%. Legend: CP – clay plug, TU – Tuyère, FF – furnace fragment, H – hearth fragment, TC – unidentifiable technical ceramic

ppm		CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3
local raw clay	KDTTS	15	12	43	22	905	755	bdl	35	15
	KDTRF	bdl	bdl	20	108	800	806	bdl	bdl	bdl
	STH8TK	16	16	34	25	782	756	bdl	bdl	bdl
Technical ceramics	KDT2CP001	11	14	28	24	744	489	bdl	74	11
	KDT2CP002	11	10	17	13	832	345	bdl	4	bdl
	KDT2FF001	8	36	30	49	921	636	bdl	bdl	bdl
	KDT2FF002	7	37	30	55	917	634	bdl	82	bdl
	KDT2FF003	84	45	58	52	722	865	bdl	36	bdl
	KDT2TU001	23	31	21	33	839	1007	7	bdl	bdl
	KDT2TU002	26	33	34	68	832	826	bdl	bdl	bdl
	Mean	24	30	31	42	830	686	-	30	-
	SD	27.2	12.9	13.3	19.4	76.3	229.2	-	32.9	-
	CV	112	44	42	46	9	33	-	118	-
	STH8T1TU	12	17	37	30	947	411	bdl	bdl	bdl
	STH8T1CP	16	27	21	15	949	330	bdl	bdl	bdl
	STH8T1FF	17	4	28	31	949	494	bdl	bdl	14
	STH8M1CP	14	bdl	12	9	872	532	bdl	bdl	30
	STH8M1FF	5	5	29	17	1014	327	1	bdl	bdl
	Mean	13	11	26	21	946	419	-	-	-
	SD	4.6	11.2	9.4	9.6	50.3	93.3	-	-	-
	CV	36	104	37	47	5	22	-	-	-
	STH8T1H	14	53	85	75	662	951	bdl	10	28
	KY5TC	5	34	21	14	750	93	bdl	bdl	bdl
	KDT1FF	0	14	26	25	555	303	7	bdl	bdl
	KDT3TU	4	22	28	51	628	189	bdl	17	bdl
	KDT3CP	7	3	9	13	904	331	bdl	38	bdl
	STH8/2TC	25	24	61	28	1003	601	bdl	156	11
	STH10CP	6	bdl	16	8	683	457	bdl	7	17
Domestic pottery	KDT2DP001	40	147	121	484	665	1430	bdl	47	30
	KDT2DP002	57	111	300	107	436	1524	bdl	40	40
	KDT2DP003	40	96	254	137	484	2511	bdl	44	bdl
	KDT2DP004	56	106	192	184	438	3913	bdl	193	24
	KYKi	24	83	217	36	482	714	bdl	70	27
	NC4Kh	9	59	144	54	566	685	10	14	7

Table 8.7 Selected trace oxide concentrations of selected ceramic related samples determined by WD-XRF and normalised to 100%.

From the findings discussed above, it is possible to tackle issues concerning the production of technical ceramics and how they are different from domestic pottery.

All technical ceramics tend to have been produced from very similar recipes of quartz and alumina-rich clay. Relatively small variations in the SiO_2:Al_2O_3 ratio are probably related to variable quartz (SiO_2) contents (Figure 8.29). Plotting this ratio against FeO, the samples are shown to loosely cluster in one large area (Figure 8.30). Based on these two diagrams, samples coming from the same site form a tighter cluster (KDT2, STH8, and KDT3) but, overall, most samples tend to overlap with each other.

To better explore the possible existence of sub-groups based on their chemistry, principal component analysis (PCA) was employed. This multivariate statistical method can facilitate exploration of relationships between variables and samples by reducing the number of chosen variables and generate factors which are used to explain trends between samples. As a result, groups may be identified by the multivariate factors generated.

The result of the PCA again shows a large cluster formed by the majority of the technical ceramics (Figure 8.31). The hearth sample and two KDT2 samples are exceptions, as they plotted far from the technical ceramic cluster. For the hearth sample, this may be due to an absorption of fuel ash components as seen in the graphs that shows an association with P_2O_5. The two KDT2 samples are shown to be richer in FeO and MnO, perhaps due to contamination from the charge.

Again, the result of PCA does not reveal clear groups among the samples. Only STH8 samples form a relatively tight group, while the rest of the samples tend to disperse. This is consistent with the relatively large chemical variation also suggested by the high CVs for most oxides (Table 8.6 and 8.7).

The possible clay sources exploited for the production of technical ceramics remain unconfirmed. Comparisons between clay and technical ceramics of KDT2 (Figure 8.33) and STH8 (Figure 8.34) indicate that the clay samples from both sites are chemically different from their technical ceramics – even if the differences are not very large.

Lastly, comparison between technical ceramics and domestic pottery confirms that they were made of different clays. One explanation may be related to the functionality of the materials. Technical ceramics were made of heavily quartz tempered clay paste possibly in order to be able to survive the metallurgical operation. Domestic pottery in contrast was made of clay pastes poorer in quartz so that finer shapes could be achieved. Exploitation of different clay sources may also explain this difference between the two materials.

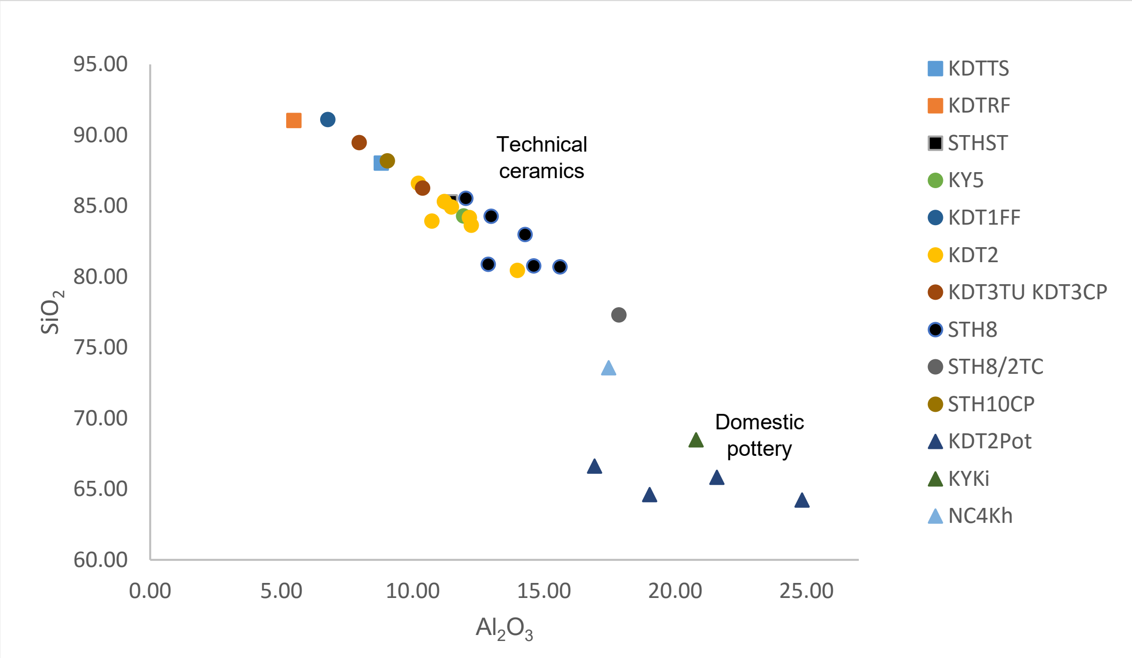


Figure 8.29 Scatter plot shows SiO_2 and Al_2O_3 values (wt%) of ceramic-related samples. Calculated from WD-XRF data normalised to 100% (Table 8.6).

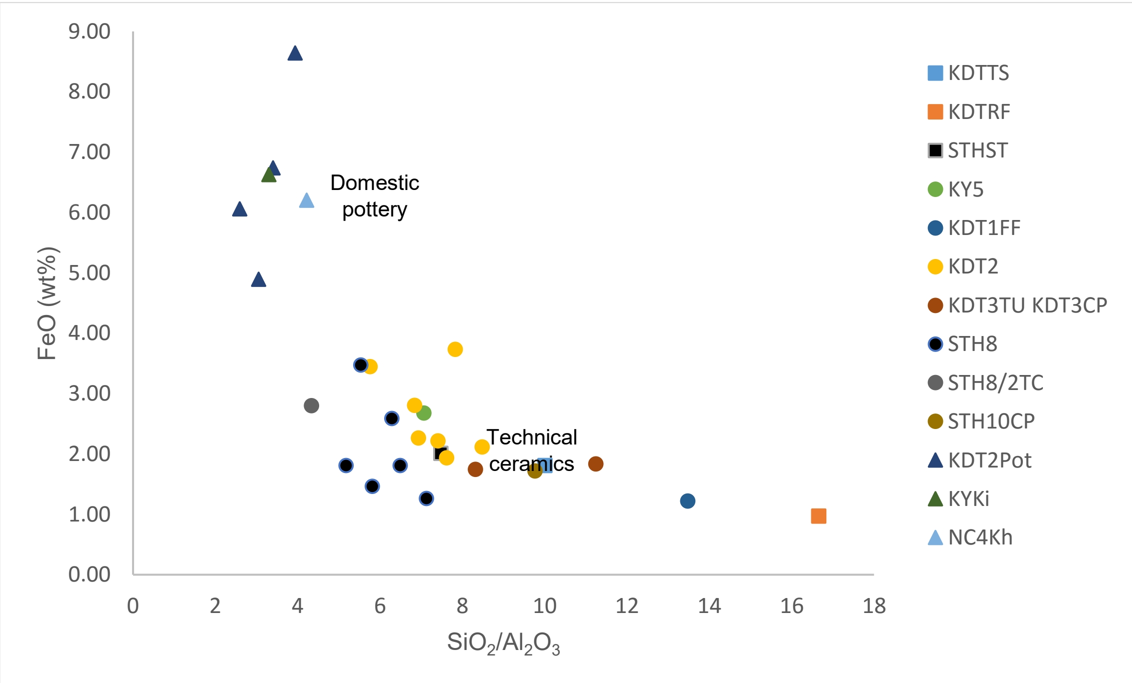


Figure 8.30 Scatter plot shows SiO_2 and Al_2O_3 ratio and FeO values of ceramic-related samples. Calculated from WD-XRF data normalised to 100% (Table 8.6).

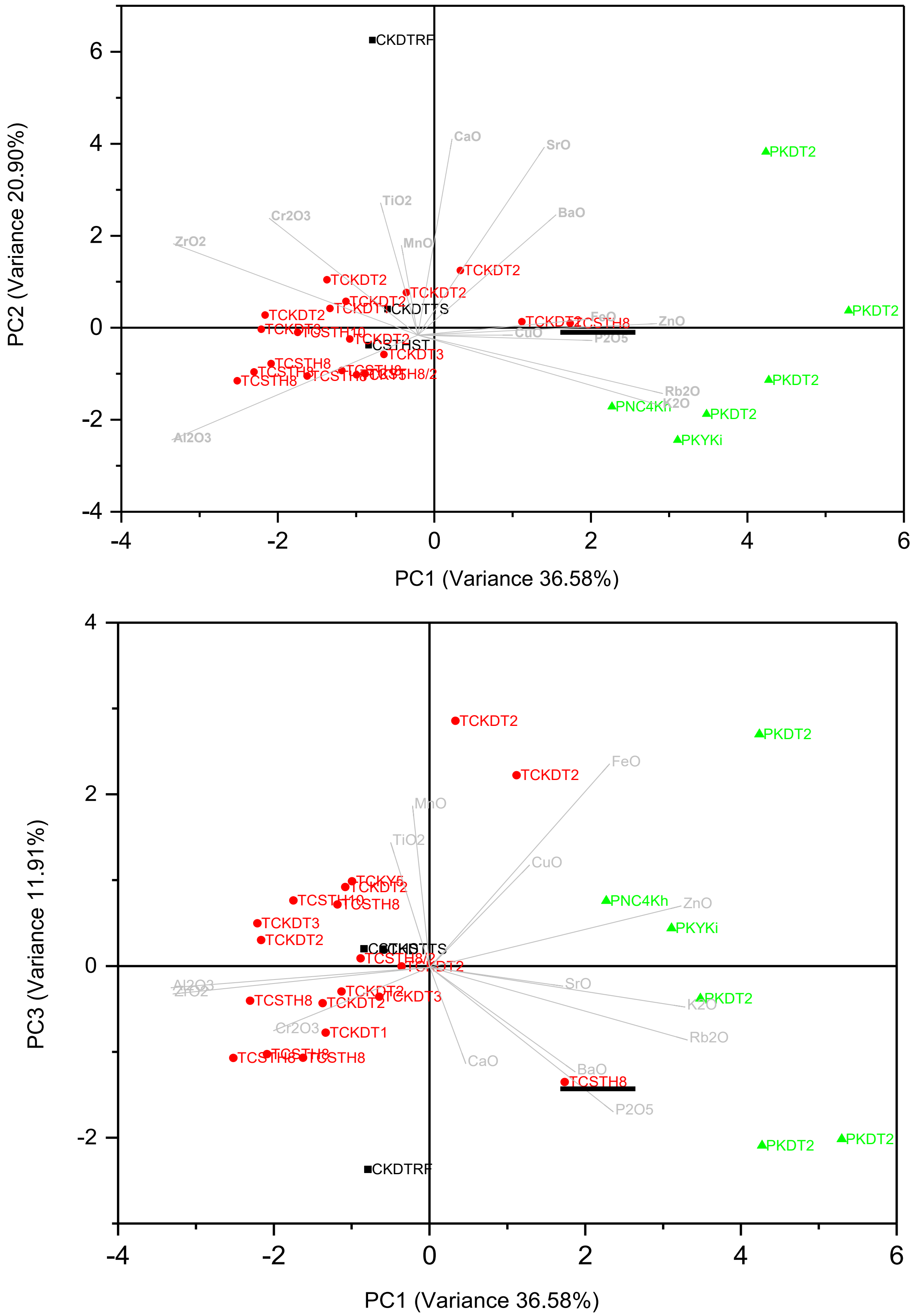


Figure 8.31 Graphs of technical ceramic (red), clay (black), and domestic pottery samples (light green) in principal component space (PC1 VS PC2 and PC1 VS PC3). The sample marked with a black line is the hearth sample from STH8 T1. The values were divided by SiO_2 to remove the dilution of quartz. La_2O_3, Ce_2O_3, and Nd_2O_3 were excluded in order to increase the variance explained by the first three components up to more than 60%, but the patterns observed with these oxides included in the analyses remain broadly the same.

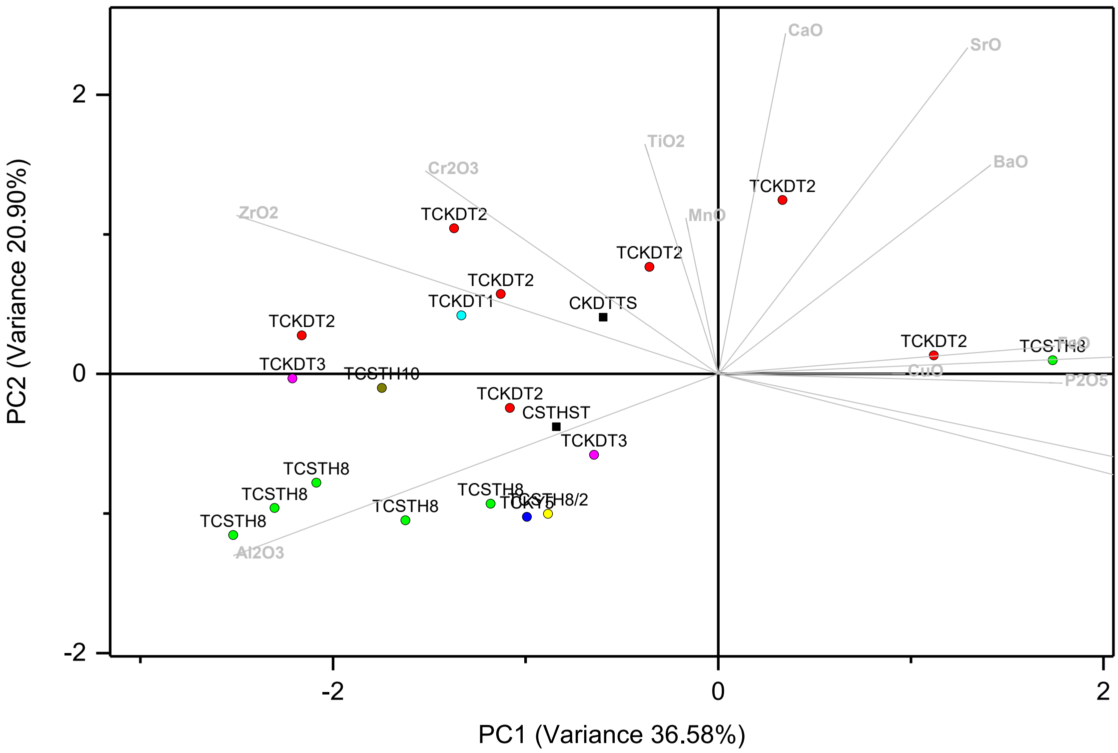


Figure 8.32 The same graph focuses on all technical ceramic samples in principal component space (PC1 VS PC2). The samples are sorted by the sites. Two clay samples are shown (black)

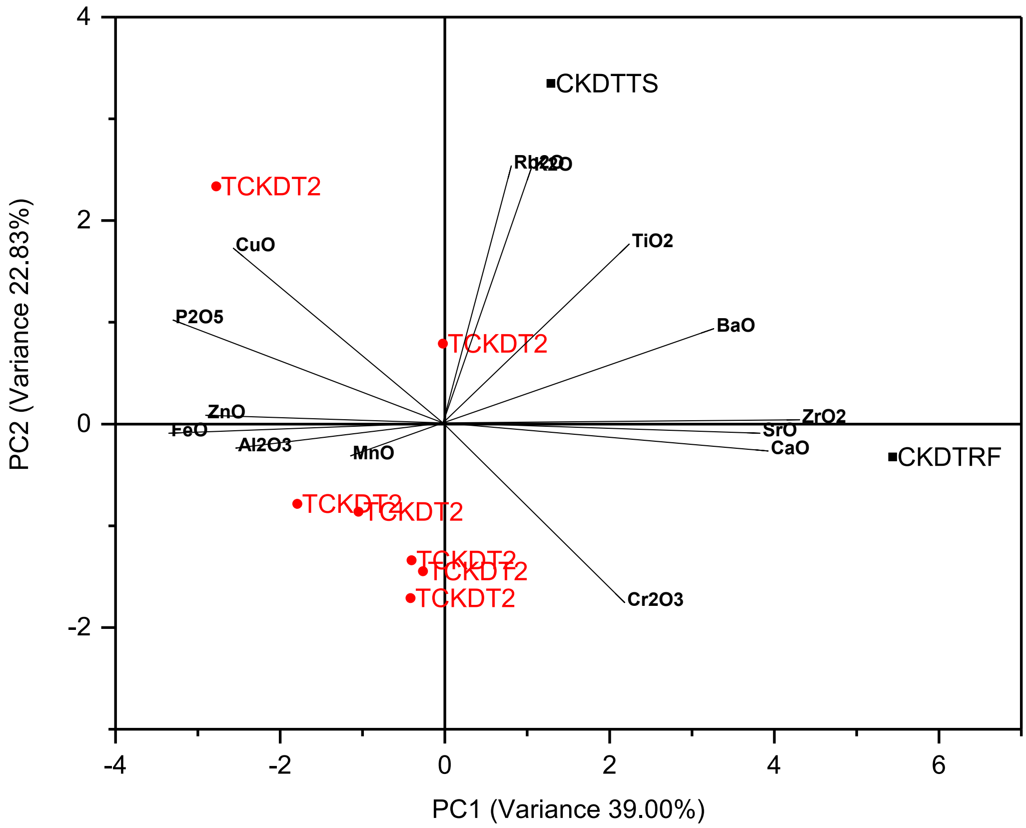


Figure 8.33 Graph of the KDT2 technical ceramic (red) and clay samples (black) in principal component space (PC1 VS PC2). La_2O_3, Ce_2O_3, and Nd_2O_3 were excluded.

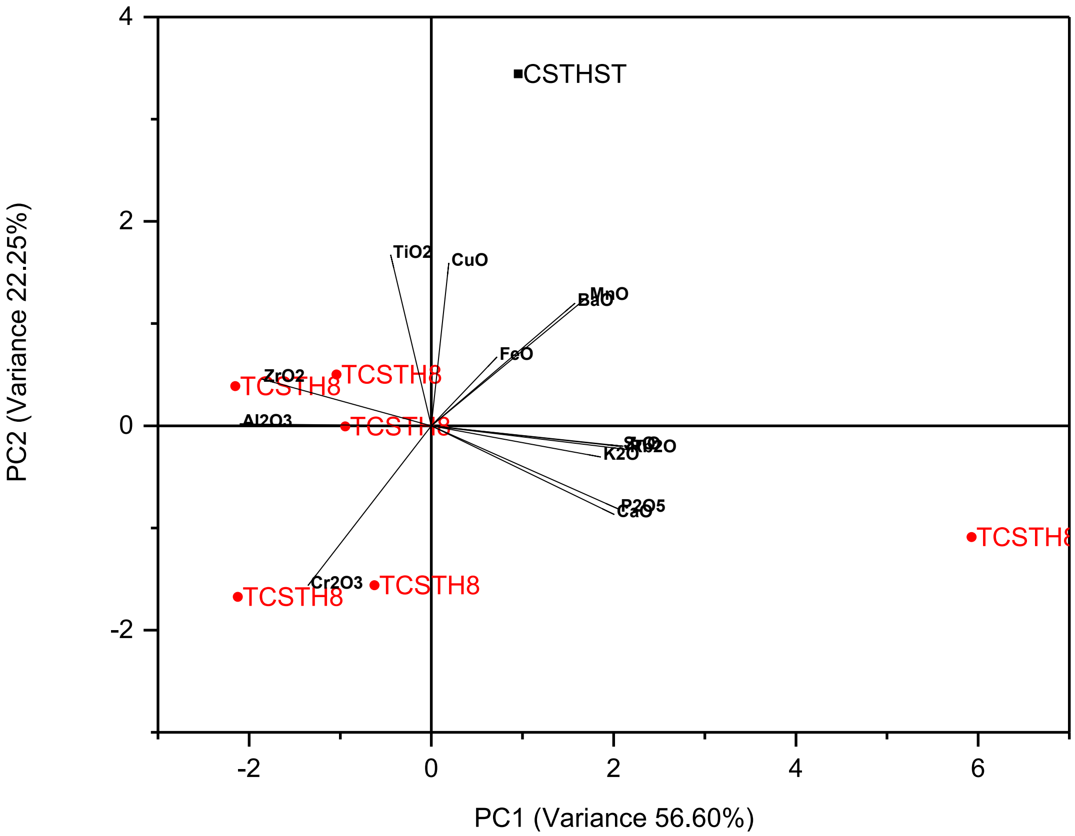


Figure 8.34 Graph of the STH8 technical ceramic (red) and clay samples (black) in principal component space (PC1 VS PC2). La_2O_3, Ce_2O_3, and Nd_2O_3 were excluded.

8.3.3 Slag

As introduced in Chapter 4, slag arguably holds the most valuable information that can be used to reconstruct the ironworking technologies in Ban Kruat. Initial macroscopic examination presented in Chapter 7 provided an initial foundation. Three discernible slag groups were identified: amorphous smelting slag, slag blocks, and convex slag. The first two slag groups are likely to be remnants of smelting activity, while the third group probably derives from smithing. More technical data about them was extracted via the structural (63 samples) and chemical analysis (109 samples).

The initial discussion of the results in this slag section is constrained to the characterisation and identification of the materials, and aims to provide relevant technical foundations; more extensive discussion on broader issues concerning the smelting mechanisms, including the formation of smelting slag and iron, are presented later in this chapter.

8.3.3.1 Smelting slag

8.3.3.1.1 Amorphous slag lumps

As introduced in section 7.3.2.1, the amorphous slag lumps can be classified into three subgroups on the basis of their overall appearance and density, and this grouping is also noticeable when they are examined in cross-section. While it is acknowledged that these are likely to represent different points of a spectrum rather than clear-cut groups, this subdivision is maintained here in order to guide the structure of this chapter. The dense slag group tends to display a uniform structure with very few pores (Figure 8.35). The second group is structurally more diverse, particularly in terms of the porosity levels (Figure 8.36). The macrostructure of the last group is almost entirely made up of pores with very little interstitial slag proper. These pores are not only more abundant but also considerably larger than in the second group (Figure 8.37). This porous structure indicates that gases generated during the smelting could not escape and were trapped. Large iron fragments were occasionally observed in some semi-porous slag samples which will be discussed later in this section (Figure 8.38).

8.3.3.1.1.1 Further structural characterisation

Microscopically, recurring phases, particularly fayalite (an iron silicate, Fe_2SiO_4), hercynite (an iron-aluminium spinel, $FeAl_2O_4$), glassy matrix, and metallic iron can be seen across the majority of the samples (Figure 8.39). Chemically, fayalite usually contains small percentages of MgO and MnO, while hercynite carries V_2O_5, Cr_2O_3, and

TiO$_2$. At the same time, some microstructural variation and additional phases are detected within each slag group.

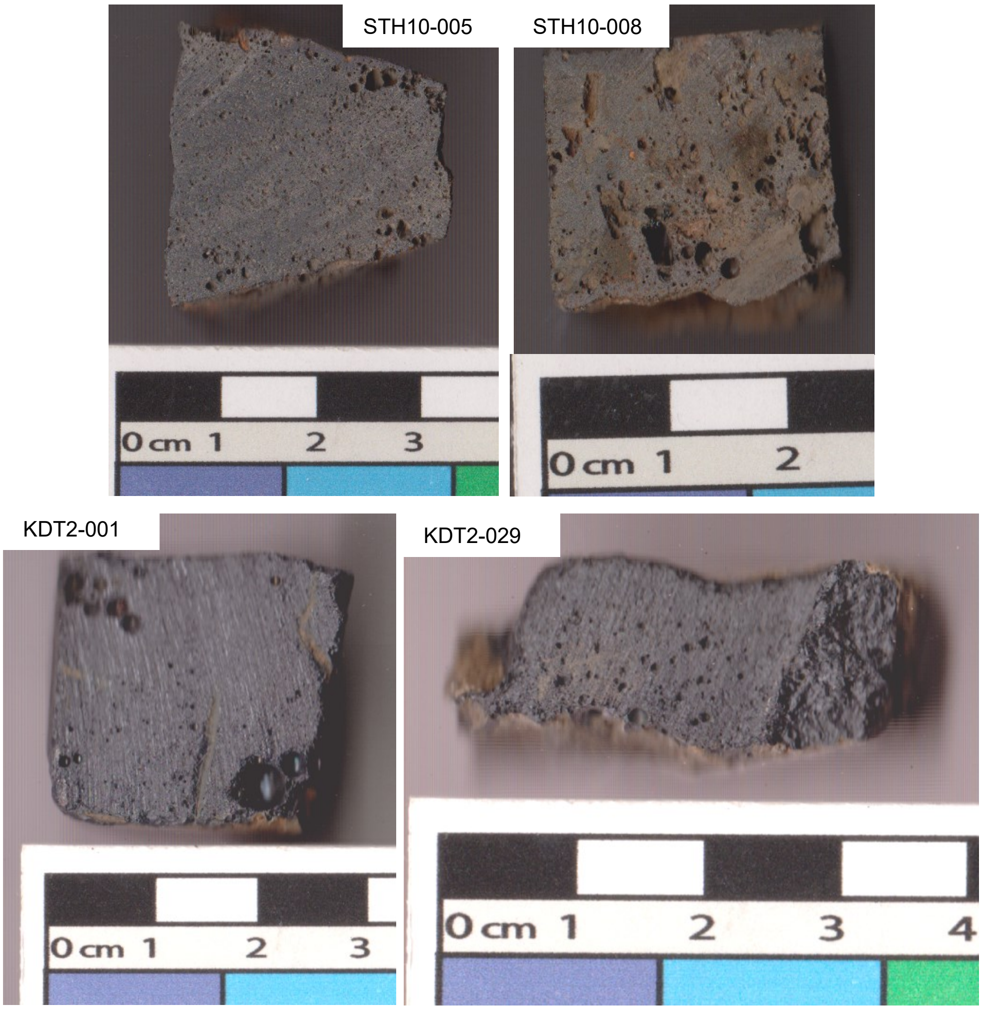


Figure 8.35 Cross-sections of some dense amorphous slag

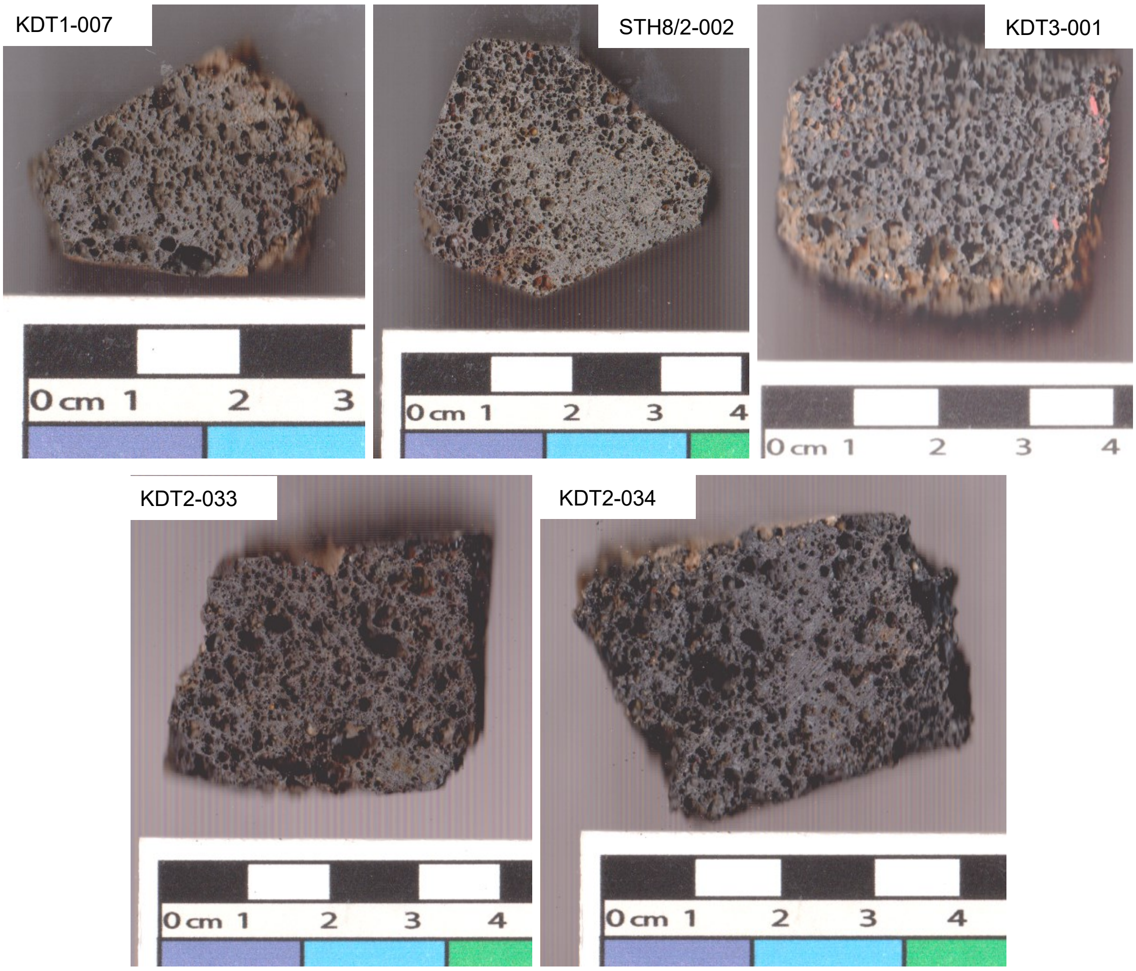


Figure 8.36 Cross-sections of some semi-porous amorphous slag

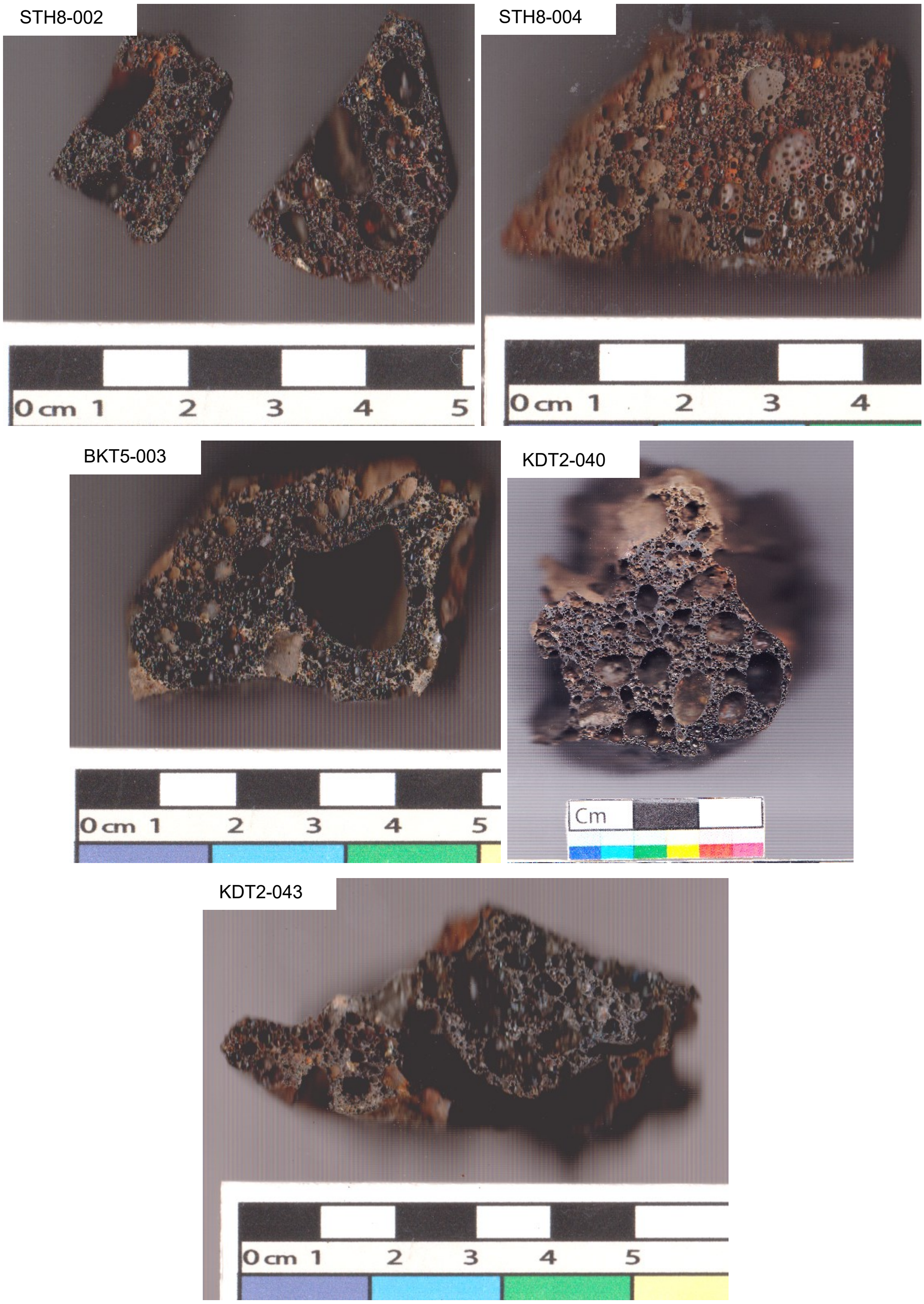


Figure 8.37 Cross-sections of some porous amorphous slag

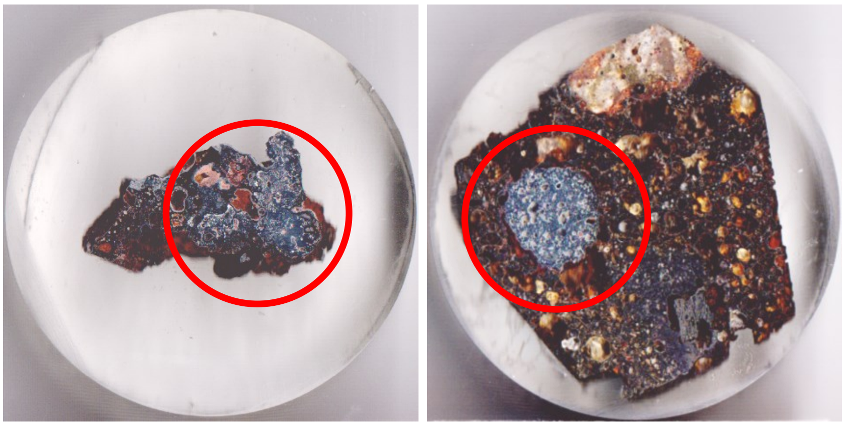


Figure 8.38 Iron fragments trapped inside slag (KY4-007 and STH10-003)

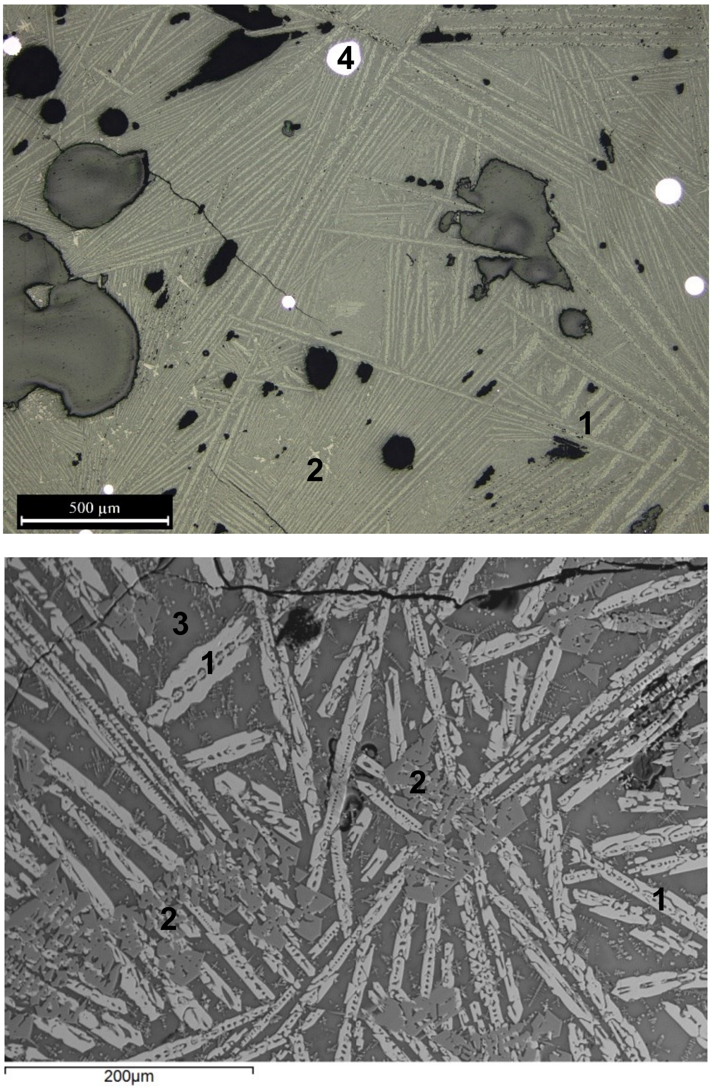


Figure 8.39 Common phases present in most specimens examined. They include fayalite (1), hercynite (2), glassy matrix (3), and metallic iron (4).

The dense slag group seems to be the most homogeneous microstructurally, systematically showing the four typical phases mentioned above (Figure 8.40 and 8.41). The fayalite crystals are usually elongated or have skeletal structure. The presence of these lath-shaped olivine phase implies that solidification occurred relatively fast and did not allow the growth of larger, euhedral crystals. However, this fast cooling does not make this slag a result of tapping, since macroscopic features (e.g. lack of flowing pattern) seem to contradict this shape of fayalite (see section 7.3.2.1), and the excavation of furnace remains at KDT2 failed to identify any tapping holes. Furthermore, other microscopic features that are diagnostic of tapping, such as oxidised surfaces or interfaces between layers (often dominated by magnetite), are not found here. Hercynite crystals always superimpose fayalite as they solidified first. Their presence indicates a relatively high alumina content in the system that could be derived from ores or technical ceramics, as discussed below. Metallic iron particles, mostly smaller than 200μm in size, are almost all globular. This may be indicative of a high carbon content leading to the formation of iron as prills, instead of as pseudomorphs of the wüstite dendrites from which they derived. Detailed discussion of these metallic iron particles in slag and their implications for our understanding of the smelting mechanisms is presented in section 8.4.

Other phases are also present, though not consistently in all samples. The first one is visible only at high magnification (above 200x) and appears growing on the surface of hercynite crystals. It is rich in FeO, TiO_2, and Al_2O_3 (Figure 8.42). These crystals might be approaching the structure of an ülvospinel (Fe_2TiO_4) (Iles and Martinón-Torres 2009), as titanium was expelled from hercynite during crystallisation, but their composition is not stoichiometric.

The second one is a feathery dendritic phase precipitating during cooling (Figure 8.43). Its chemistry is defined by three dominated oxides (SiO_2, Al_2O_3, and FeO) with ratios of 1:0.2-0.3:0.8-1. It also contains MgO, CaO, TiO_2, and MnO as minor compounds. This phase is possibly described as second generation fayalite or “devitrified glassy matrix or feathery devitrification” (see Veldhuijzen 2005, 175-176 for the same phase identified). A “bulk” chemical comparison between the areas dominated by fayalite and this phase of interest shows that they are chemically indistinguishable, despite their different shapes (Table 8.8). The presence of this phase is indicative of the phase that grew out of the glassy matrix at the very last stage of solidification, thus doing have enough time to form properly.

The third is a black phase (Figure 8.44). This phase, having relatively angular outline with internal fine structure, is always superimposed by fayalite crystals. Its chemistry is dominated by SiO_2 (45-51%), Al_2O_3 (17-27%), and FeO (20-25%) with the ratios of approximately 1:0.5:0.5. It also contains P_2O_5, CaO, V_2O_5, TiO_2 (see Appendix I for the full chemical compositions). This is relatively similar to the feathery devitrification. Owing to its underdeveloped structure and nonstoichiometric chemical composition, this phase is likely to have been formed in the same way the feathery devitrification did.

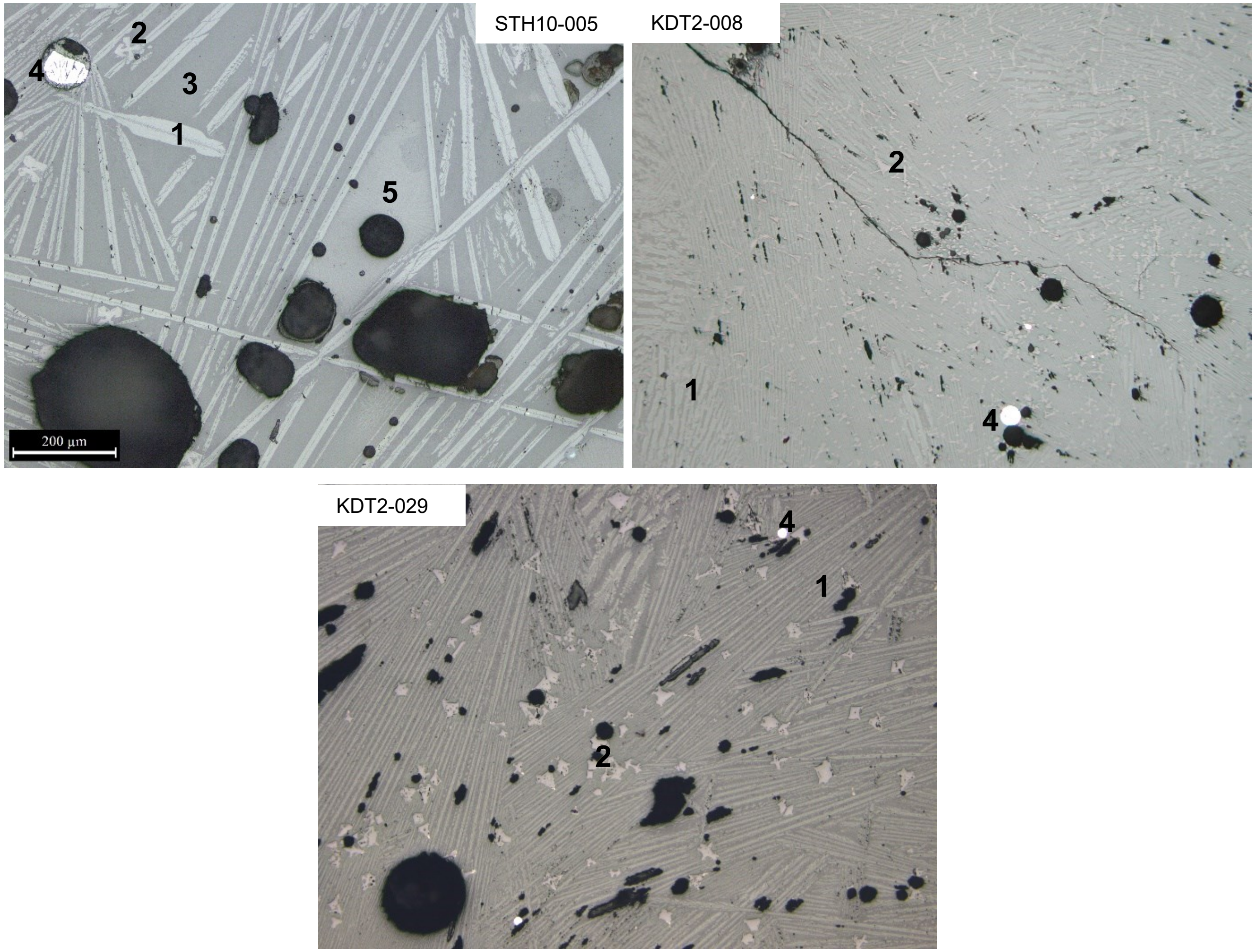


Figure 8.40 Micrographs of dense slag group. Common phases include elongated skeletal fayalite (1), hercynite (2), glassy matrix (3), and metallic iron, mainly globular (4). Devitrified glassy matrix (5) in STH10-005 was occasionally identified. The black phase is hard to see at this magnification (please see below figure). Image width ≈ 3.5mm

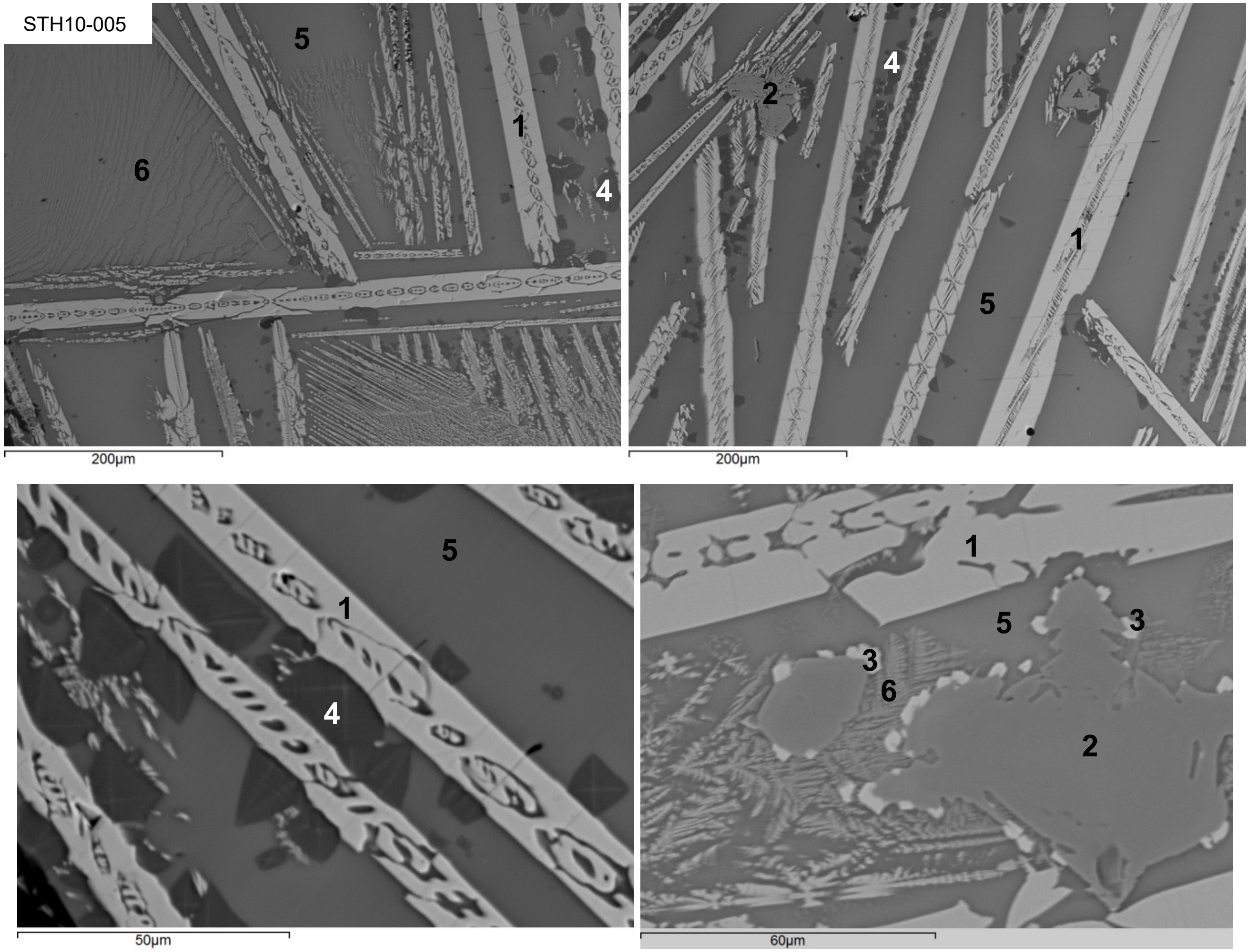


Figure 8.41 BSE images show more details on some phases in the dense slag group, including fayalite (1), hercynite (2) with the FeO-TiO_2-Al_2O_3-rich phase on its edge (lower right image) (3), the black phase (4), and glassy matrix (5). Feathery devitrification (6) and the black phase could be detected occasionally.

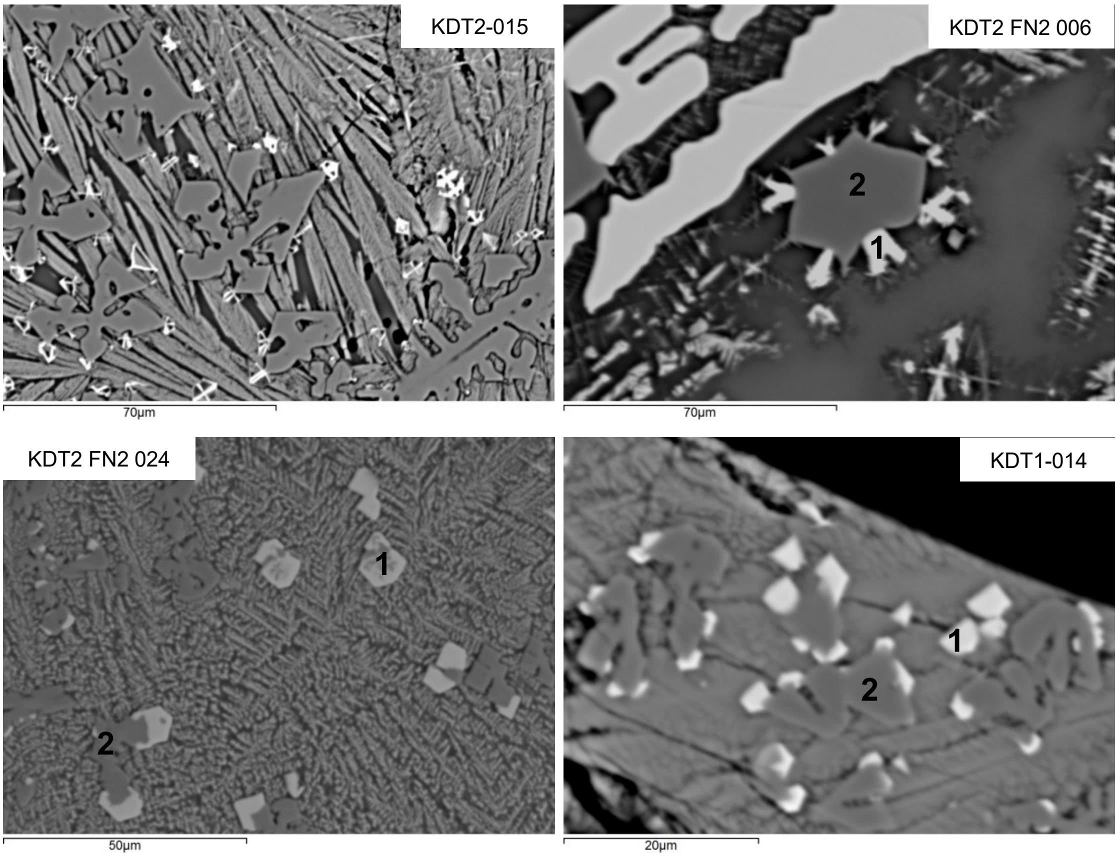


Figure 8.42 BSE images showing the FeO-TiO_2-Al_2O_3-rich phase (1) that is rich in iron oxide (57-62 wt%), titania (TiO_2 20-25 wt%), alumina (Al_2O_3 8-20 wt%), and silica and vanadium oxide (SiO_2 1-3 wt% and V_2O_5 ≈1wt%) crystallising out of hercynite (2).

Please note that, since this phase is also present in the semi-porous slag group, images were also taken from them as they provide better images for illustration. The illustration for other phases was done in the same way.

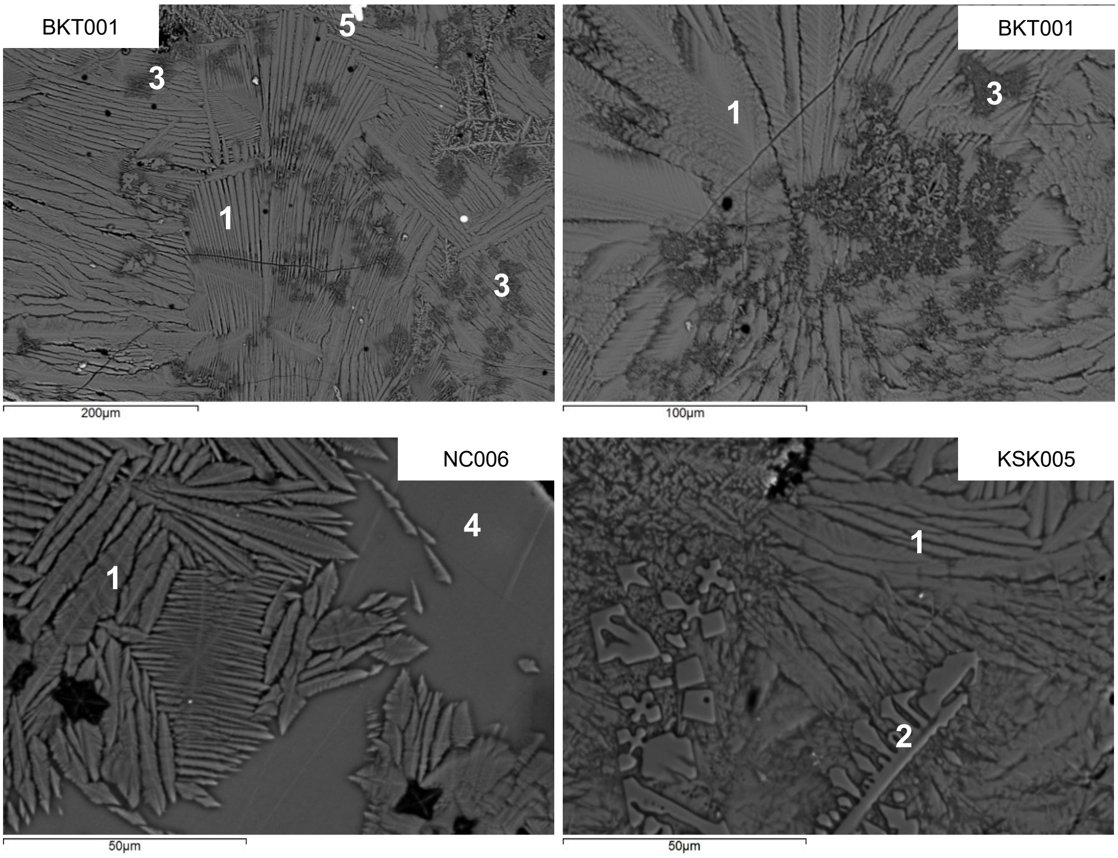
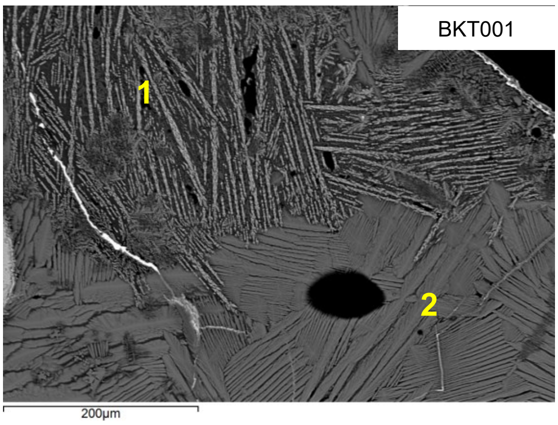


Figure 8.43 BSE images show a glassy matrix with feathery devitrification (1), hercynite (2), the black phase (3), glassy matrix (4), and iron particles (5).



wt%	MgO	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	MnO	FeO
Fayalite zone (1)	0.3	16.3	44.1	0.7	1.3	1.4	1.4	34.4
Feathery devitrification (2)	0.3	15.4	43.6	0.7	1.2	1.2	1.7	36.0

Table 8.8 A "bulk" chemical comparison between fayalite (1) and feathery devitrification (2). Data was obtained from BKT001 by SEM-EDS area analyses and normalised to 100%.

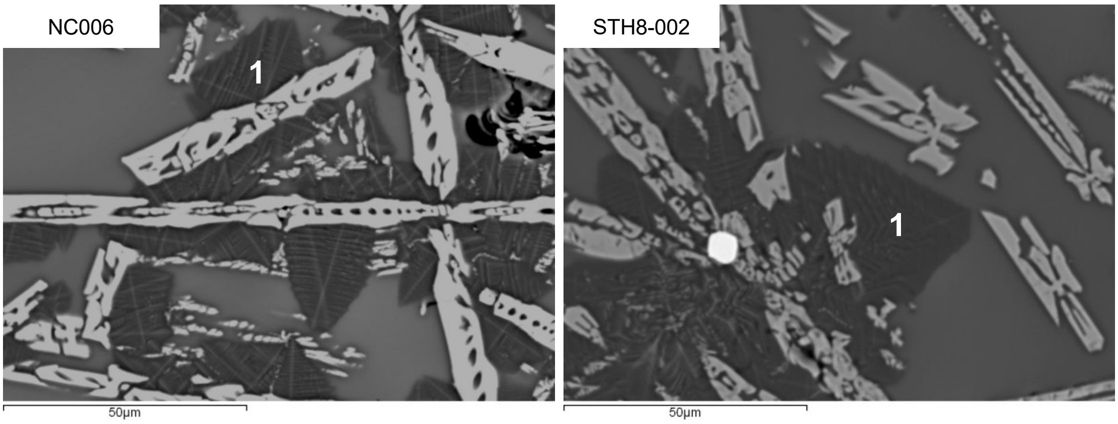


Figure 8.44 BSE images show a black phase (1) superimposed by fayalite crystals

The microstructure of the second group differs from dense slag samples (Figure 8.45 and 8.46) primarily in having less developed fayalite crystals (feathery) (Figure 8.47) and an olivine-like phase which does not present in the dense slag (Figure 8.48). The same phases seen in the previous slag group can still be seen but are more diverse in terms of phase consistency and distribution. The microanalysis indicates that the olivine-like phase, having the ratios of SiO_2-Al_2O_3-FeO approximately 1:0.1-0.2:1-0.9, is chemically similar to the feathery devitrification; however, its structure more resembles elongated fayalite crystals. Its characteristic is probably suggestive of another phase that did not have time to form into a proper equilibrium phase (fayalite), likewise the feathery devitrification and the black phase.

Lastly, in the third group, the significant difference is that abundant medium to large pores, feathery fayalite, and larger glassy matrix predominate the structure instead of developed phases (Figure 8.49). This conforms well to their macrostructure that is very light, glassy, and porous.

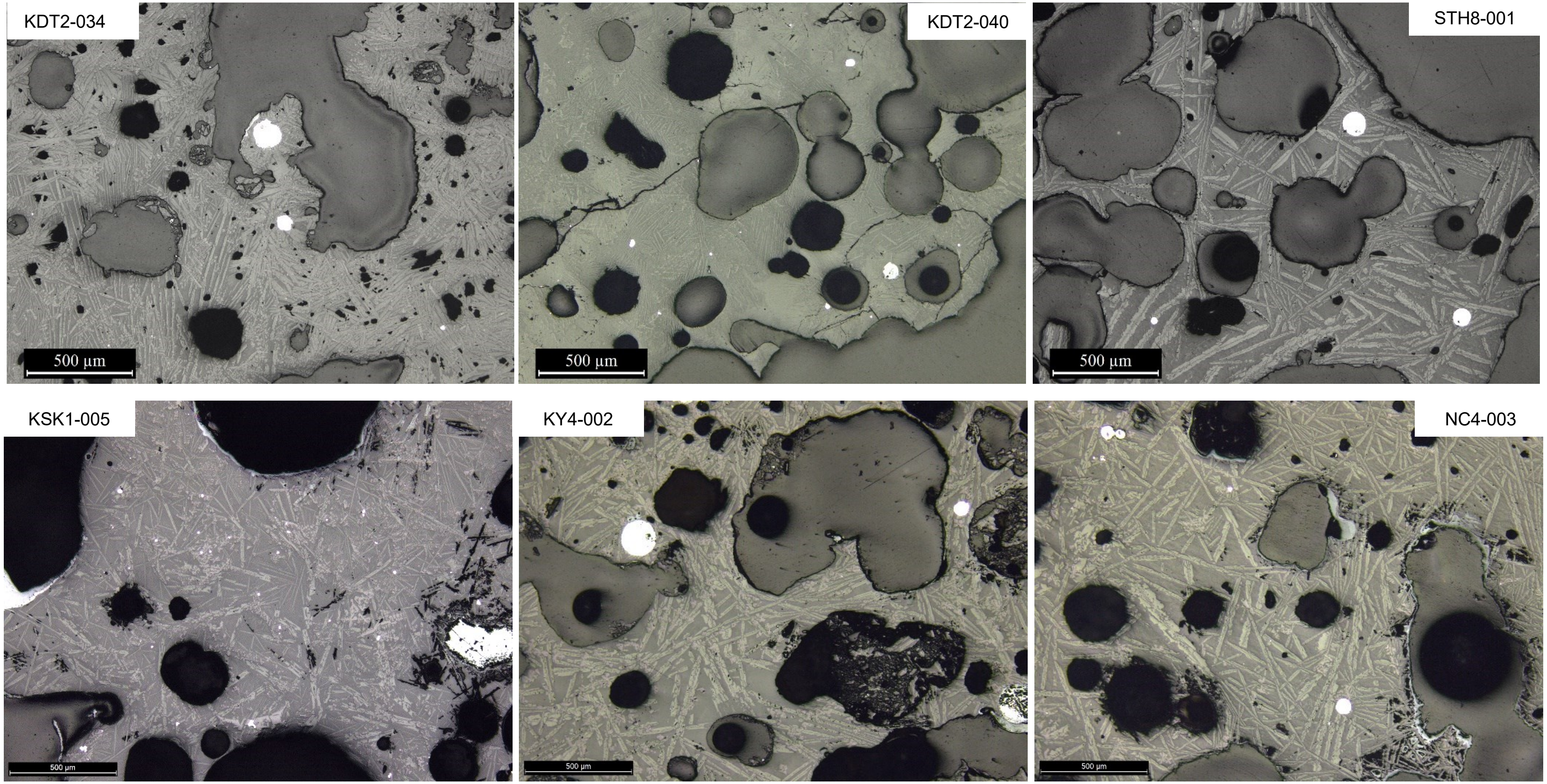


Figure 8.45 Micrographs show shared microstructure of the samples in the semi-porous slag group. The phases comprise of elongated skeletal fayalite and metallic iron, mainly globular. Hercynite, the FeO-TiO_2-Al_2O_3-rich, and black phases, and glassy matrix are better seen at higher magnification (see next figure).

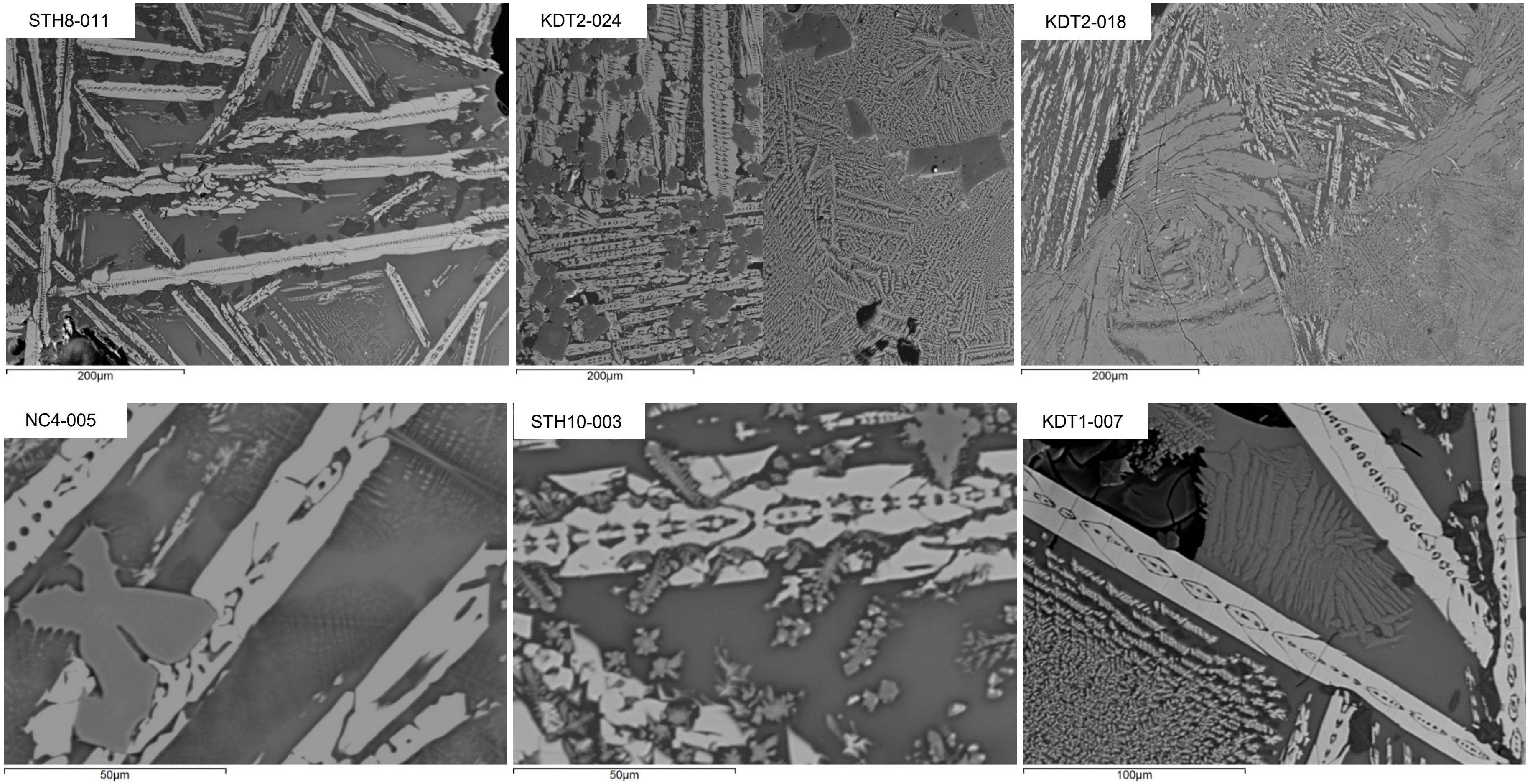


Figure 8.46 BSE images further show the phases, including fayalite, hercynite, the FeO-TiO_2-Al_2O_3-rich phase (top middle image), and glassy matrix. Feathery devitrification and the black phase could be detected occasionally. The top middle image illustrates heterogeneity in a single slag lump.

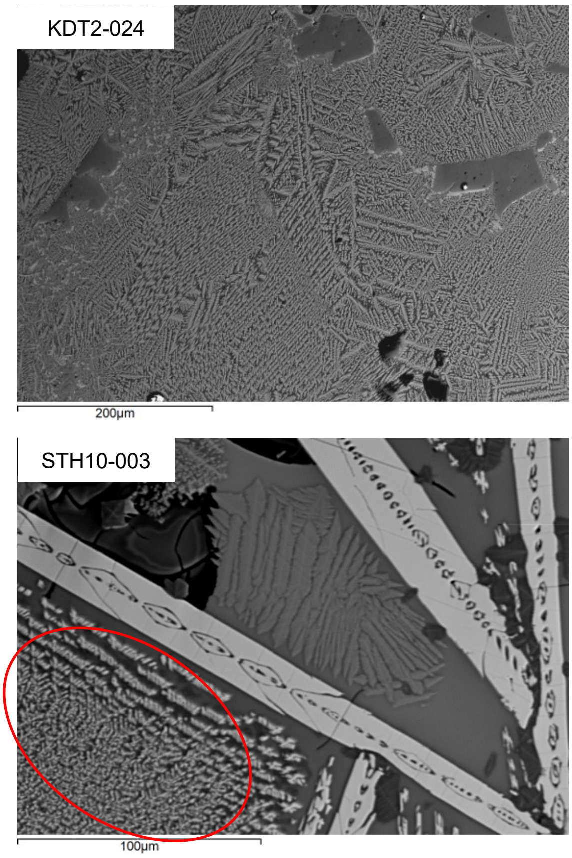


Figure 8.47 BSE images show feathery fayalite crystals

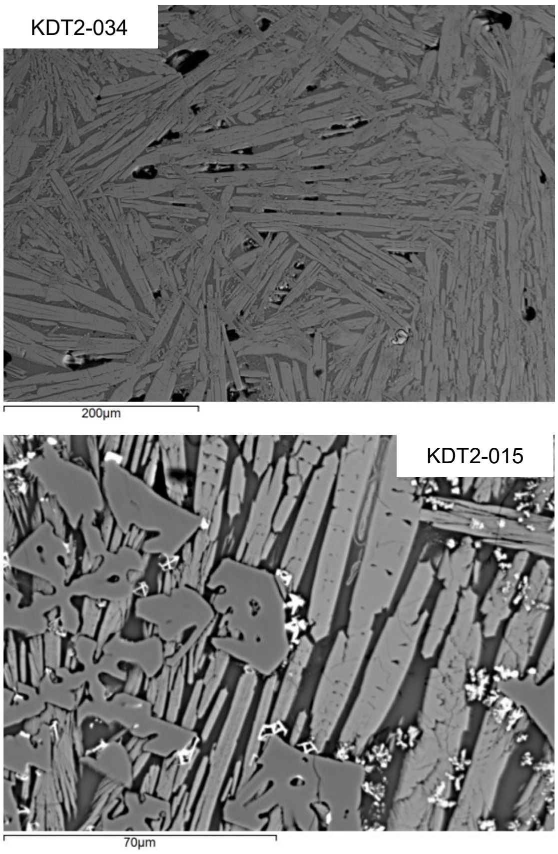


Figure 8.48 BSE images of olivine-like crystals

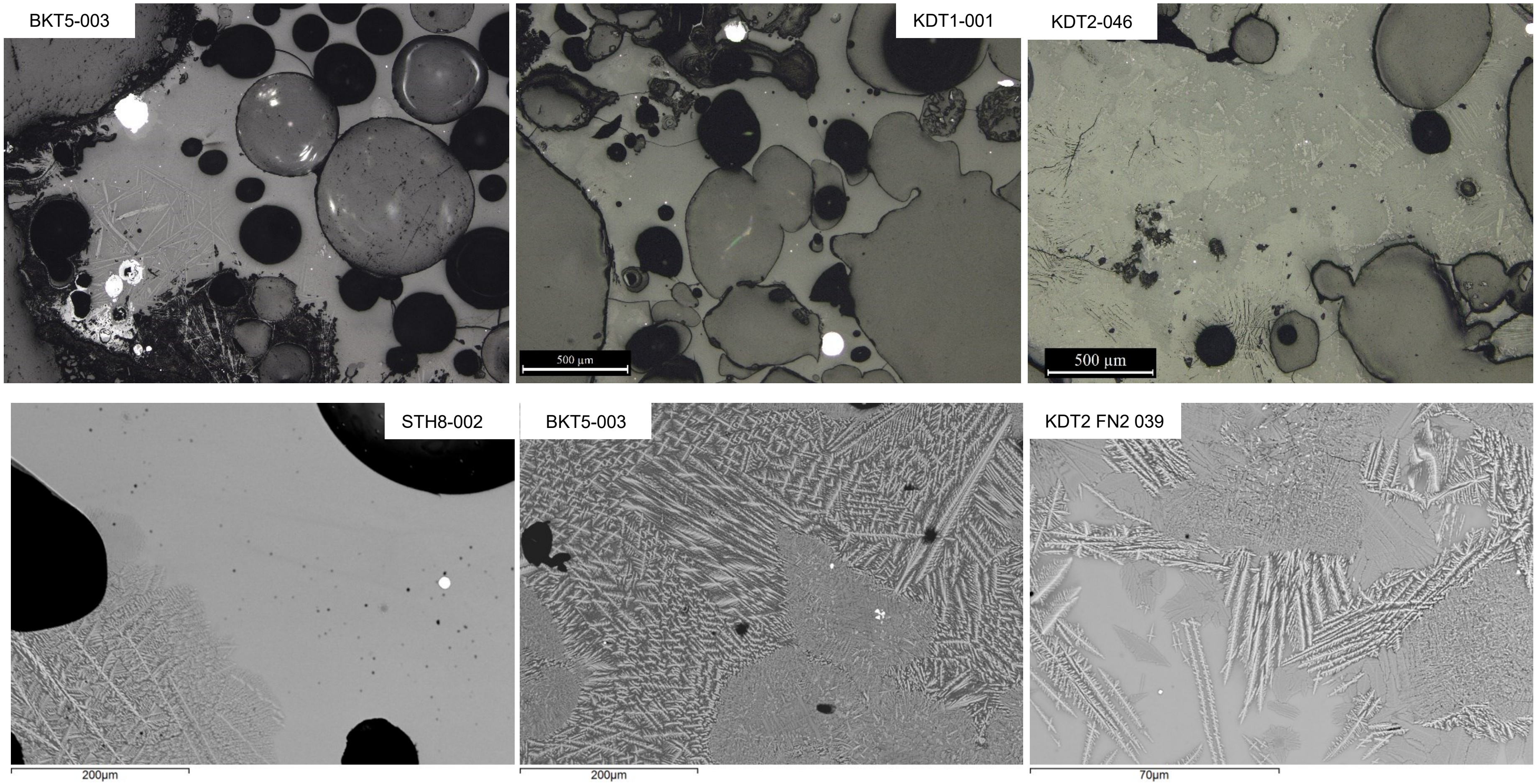


Figure 8.49 Micrographs and BSE images of porous slag group. Unlike the previous group, large glassy matrices and feathery fayalite are more common.

It is quite remarkable that free iron oxide phases, such as wüstite (FeO) or magnetite (Fe_3O_4) are completely absent in all 63 specimens analysed microscopically. This indicates that any iron oxide available in the system was consumed for the formation of fayalite, hercynite, and other mentioned phases, or reduced into metallic iron. As for metallic phases, they are present in almost all slag samples. Only a small number of metallic iron particles retain the shape of wüstite (Figure 8.51), but the majority of the metallic iron is globular or fairly rounded (Figure 8.50). The shapes strongly suggest that iron was relatively molten which created a round shape instead of typical wüstite shape. The formation of these prills indicates that the metal is iron alloyed with a considerable amount of carbon, which would have lowered the melting point from the 1,538°C of pure iron to temperature ranges more typical of ancient smelting furnaces (approximately 1,200°C) (Figure 8.52). To confirm the carbon-rich nature of these prills, a few samples were etched to examine iron particles metallographically. Unfortunately, all prills failed to exhibit any microstructures, possibly because they have a single crystal structure, thus not showing differentiation in crystal orientation. It should be emphasised that this does not mean that all the iron produced in these furnaces would have become fully liquid, as is the case in blast furnace smelting; it is possible that iron particles may have been molten and carburised before conglomerating into larger prills (Figure 8.53) or inclusions (Figure 8.54) and eventually coalescing in a bloom.

Apart from these presumably carbon-rich iron particles, one grey cast iron (Figure 8.55) and four phosphoric white cast iron phases (Figure 8.56-8.58) (see Rostoker and Bronson 1990, 17; Scott 1991, Chapter 8) were also identified among larger iron fragments (visible to naked eyes) found in eight slag samples. These are in addition to one grey cast iron prill identified in a slag sample in the pilot study (Venunan 2011, 64) (Figure 8.59). A main difference between them is seen via the distinctive microstructures (e.g. the presence of carbon in iron) which gives a name to each type. While both types are quite similar in terms of their carbon contents (grey – 2.5-4.0% C and white – 1.8-3.6% C (Radzikowska, 2004, 565)), white cast iron has the carbon in the form of carbides (Fe_3C) (white crystalline fracture) instead of graphitic carbon structure (black flakes) in grey cast iron (Davis 1996, 3-15).

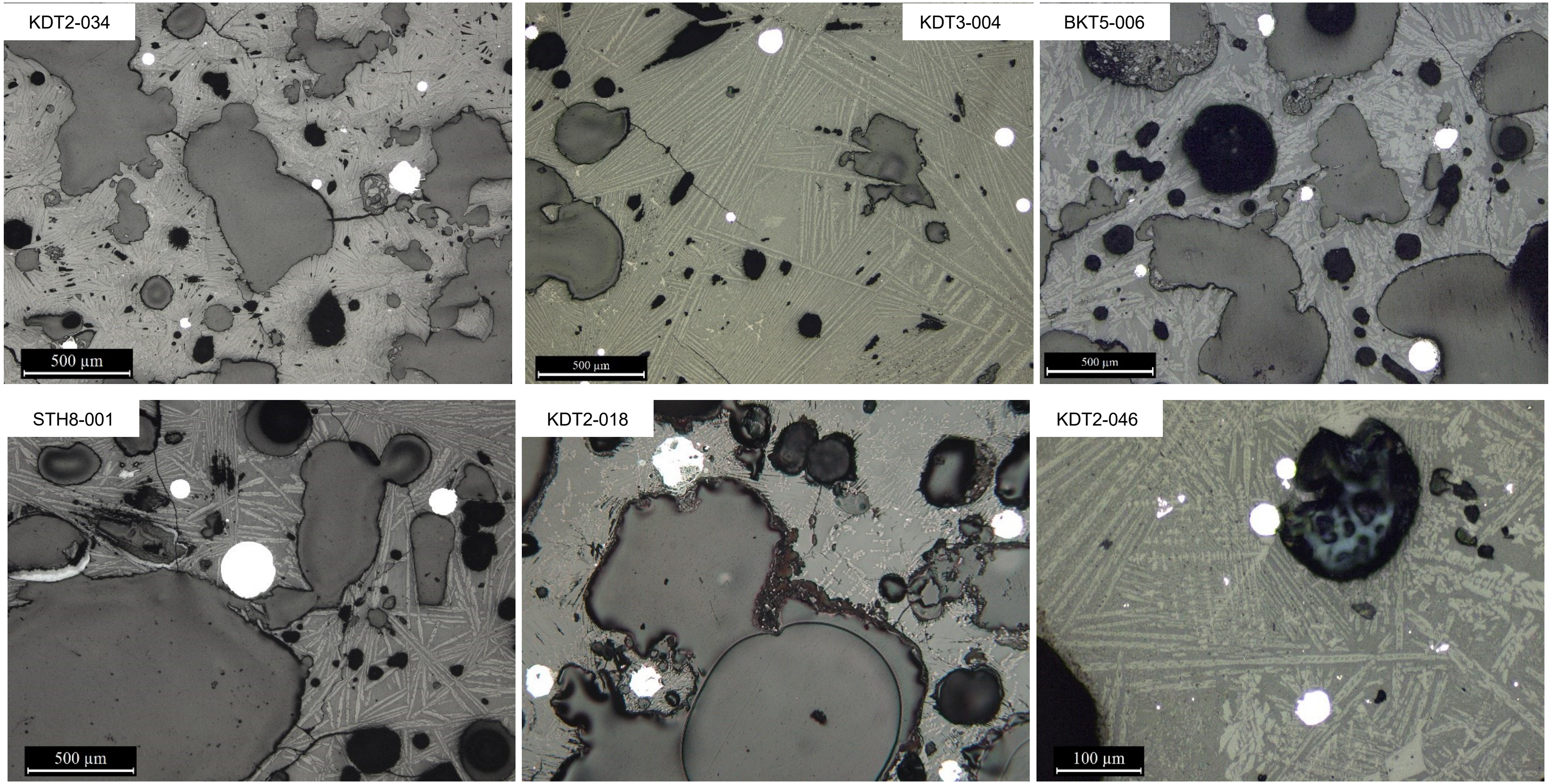


Figure 8.50 PPL micrographs showing metallic iron prills (white). Iron prills are mostly observed in the second and third group.

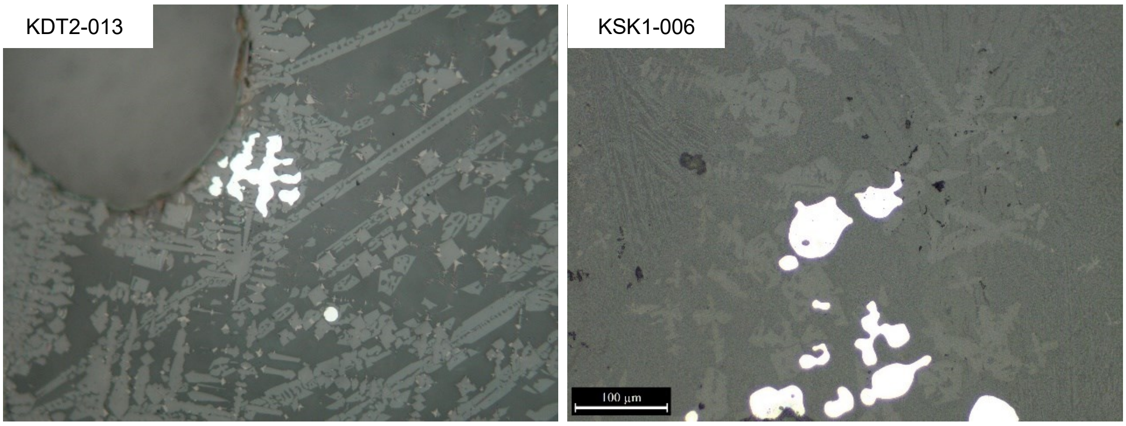


Figure 8.51 Metallic iron as pseudomorphs of the wüstite dendrites. Of 63 samples, only two samples offer these examples.

Figure 8.52 Fe-C binary phase diagram

(Image: http://www.sv.vt.edu/classes/MSE2094_NoteBook/96ClassProj/examples/kimcon.html)

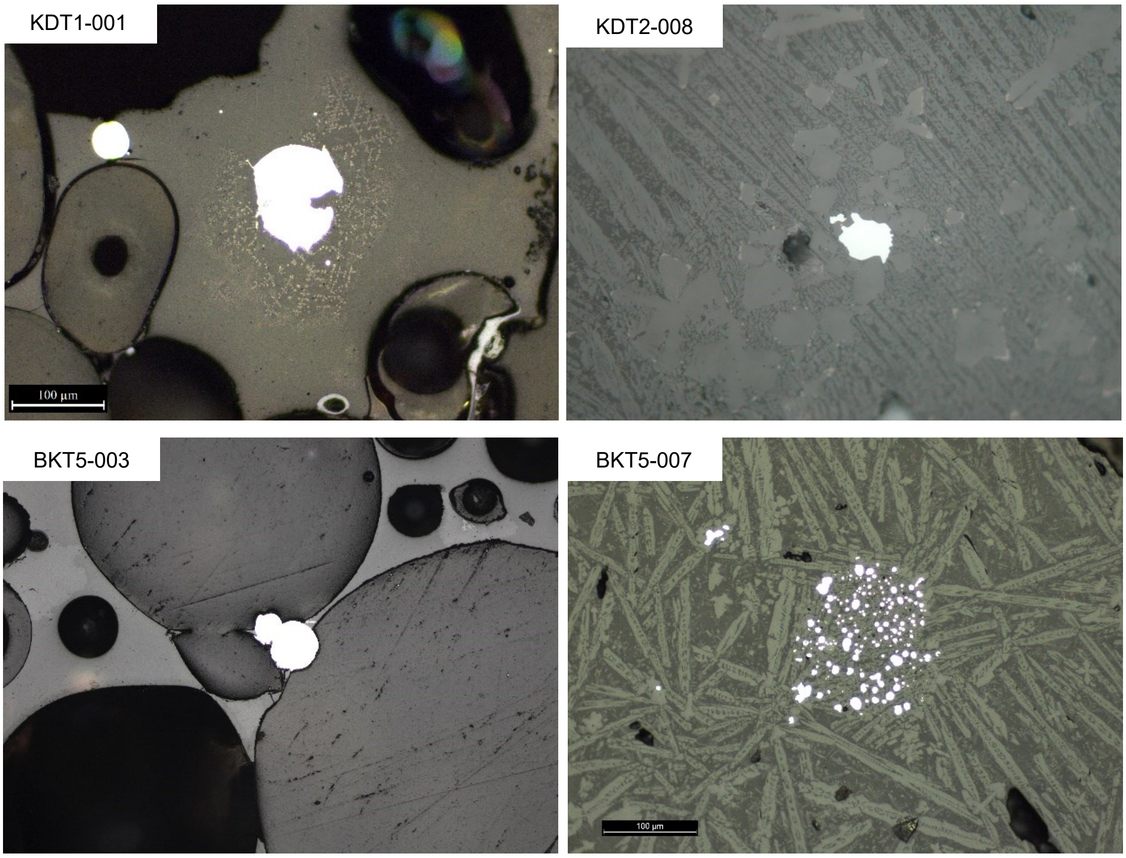


Figure 8.53 Micrographs show a conglomeration of small iron prills/particles into larger ones

(Image width ≈ 0.85mm)

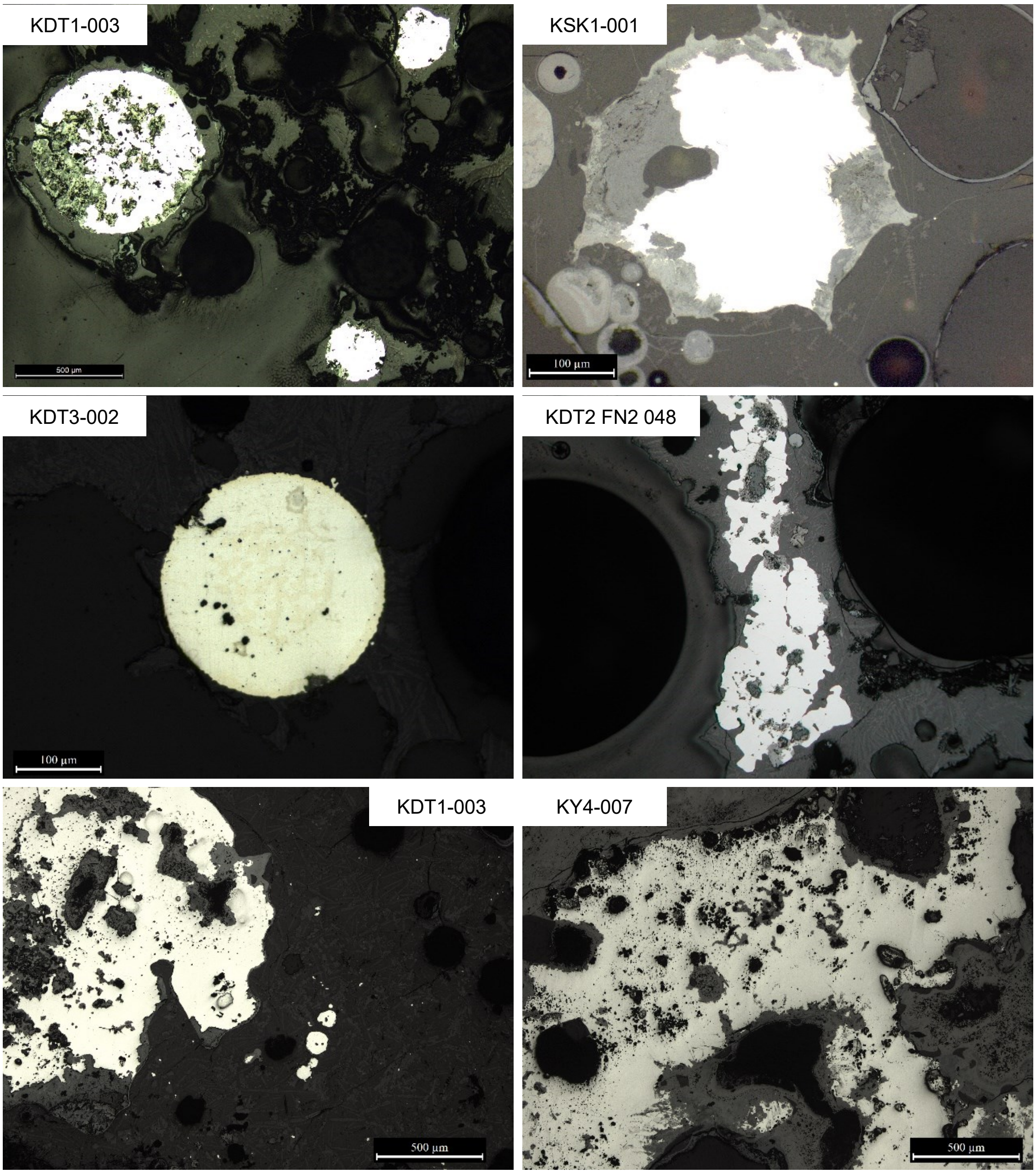


Figure 8.54 Larger iron prills/particles seen in slag

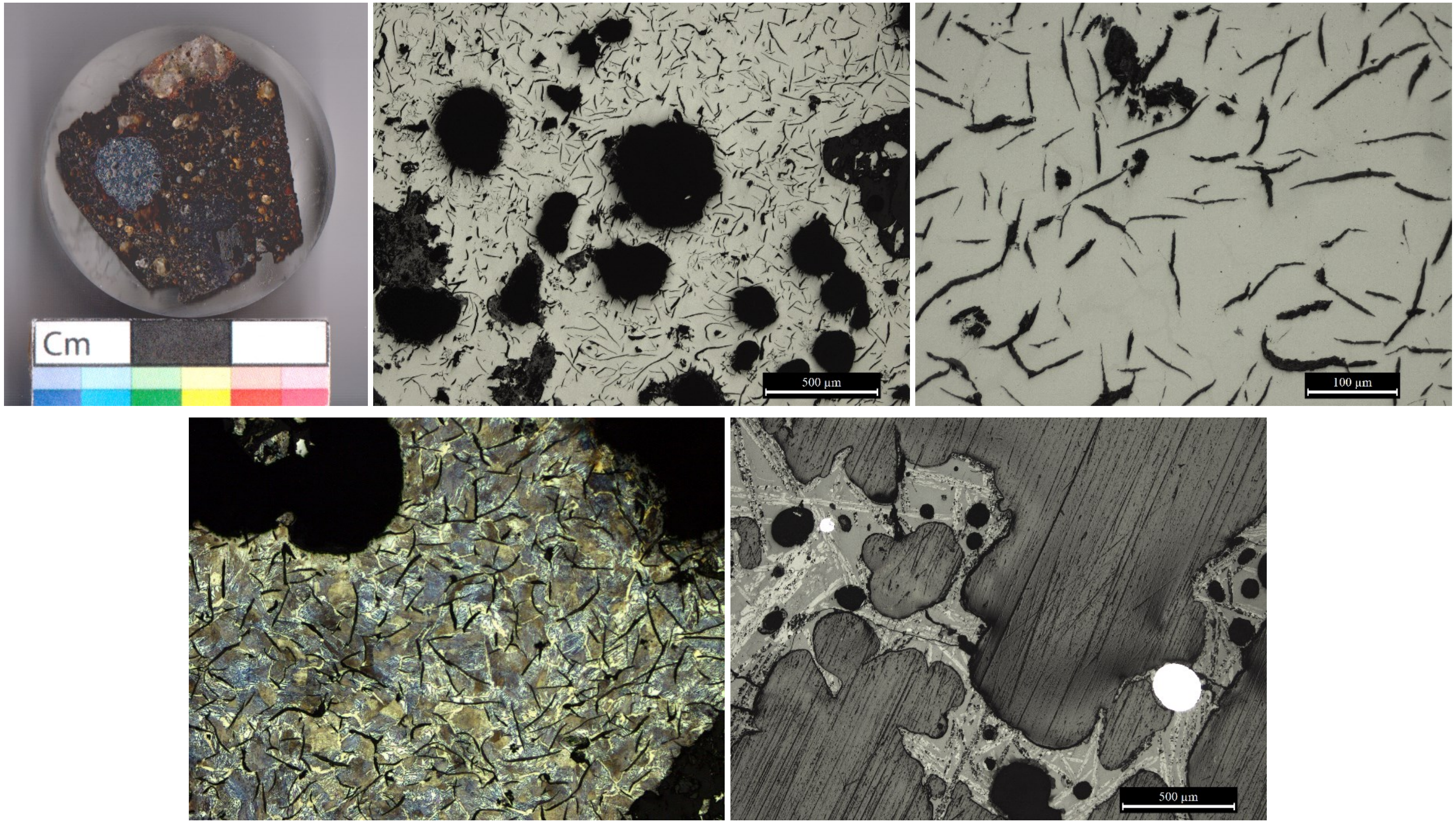


Figure 8.55 Grey cast iron fragments found in STH10-003. Graphite flakes in iron are characteristic of this type of iron alloys (Davis 1996, 36). Smaller iron prills are seen in the lower right image.

Image width ≈ 0.85mm

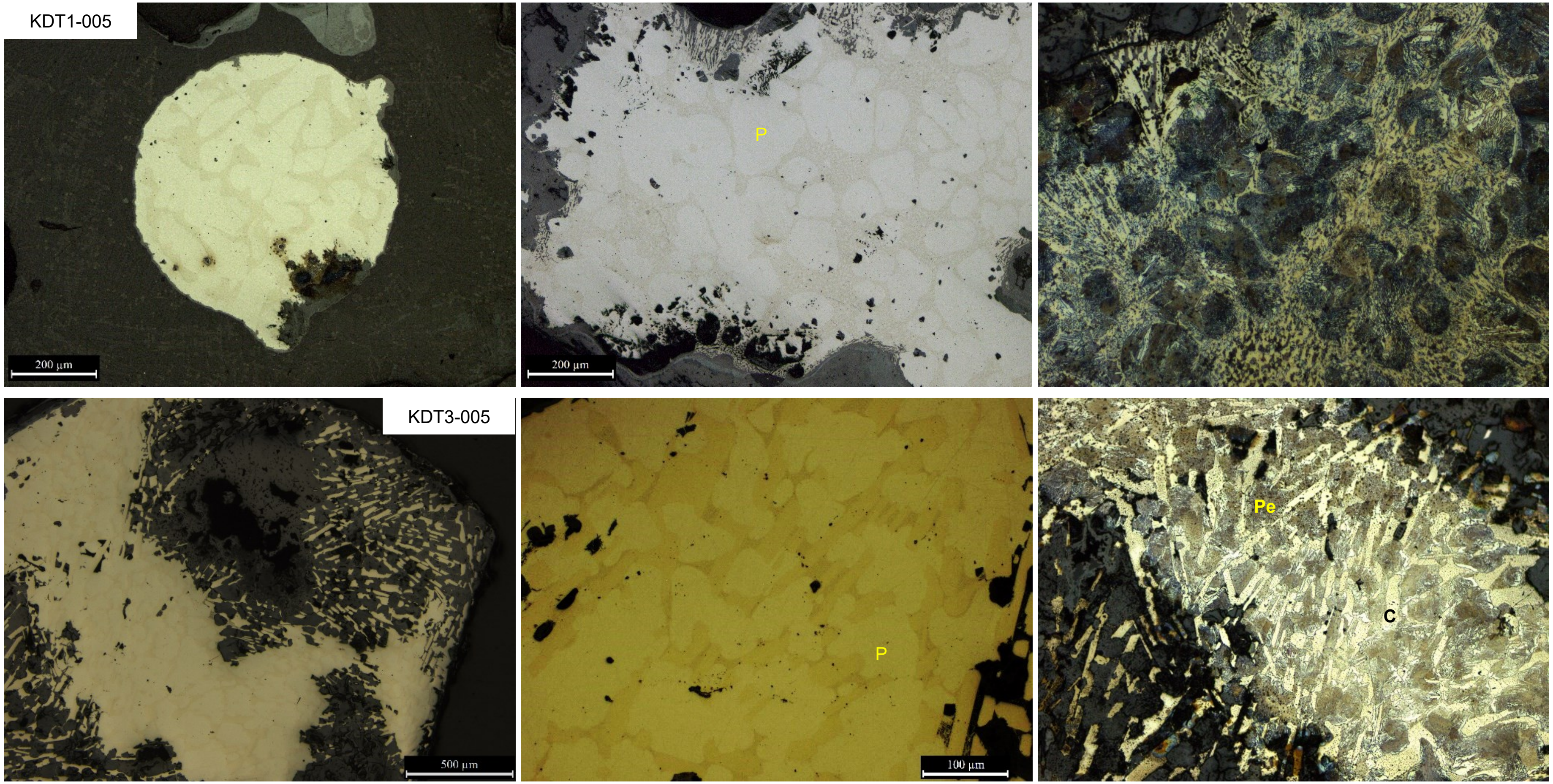


Figure 8.56 The microstructure of iron fragments trapped in slag. The examinations describe them as phosphoric white cast iron. The existence of long cementite (white-C) and pearlite (dark-Pe) helps the classification of this alloy. A phosphoric nature of iron was identified by a segregated round/sub-angular white phase (P) dispersing across the microstructure (Bailey 1982, 25; Radzikowska 2004). Image width ≈ 0.85 (top) and 1.75mm (below)

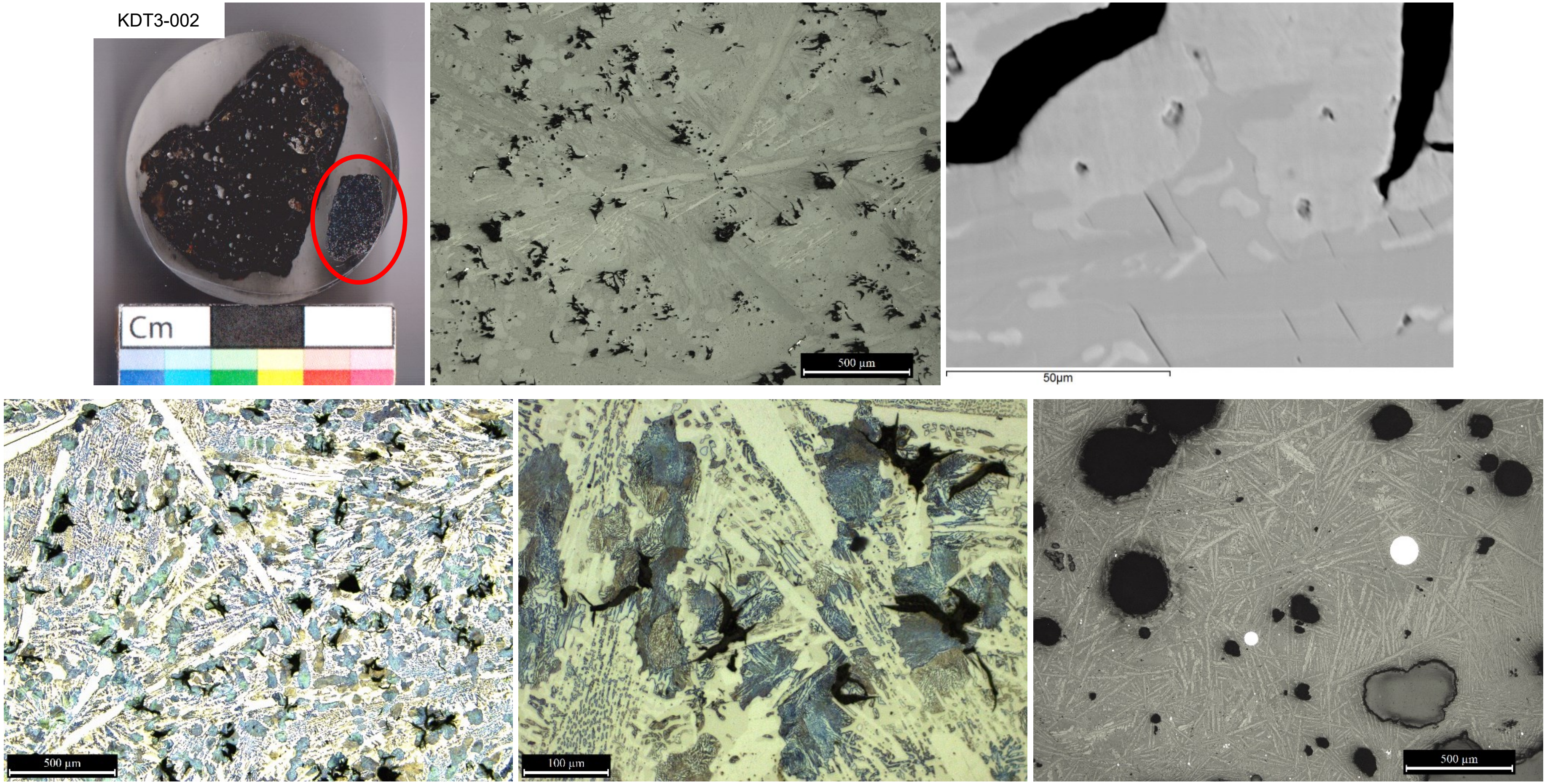


Figure 8.57 Large phosphoric white cast iron fragments remaining in slag (see Figure 8.56 for more discussion). The lower right image shows other iron prills in the same slag sample.

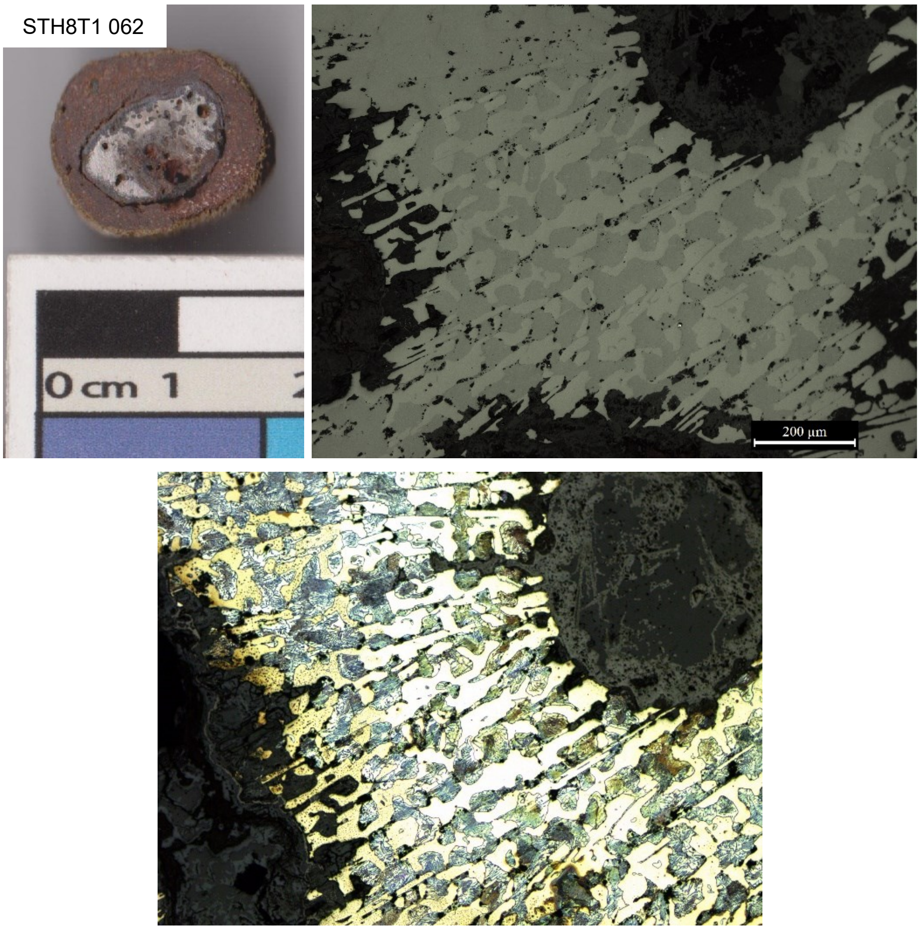


Figure 8.58 A fragment of phosphoric white cast iron found at STH8 T1, associated with smithing context. Interestingly, it was enveloped by clay-like material, looking very similar to laterite nodules found at the same area. Image width ≈ 1.75mm.

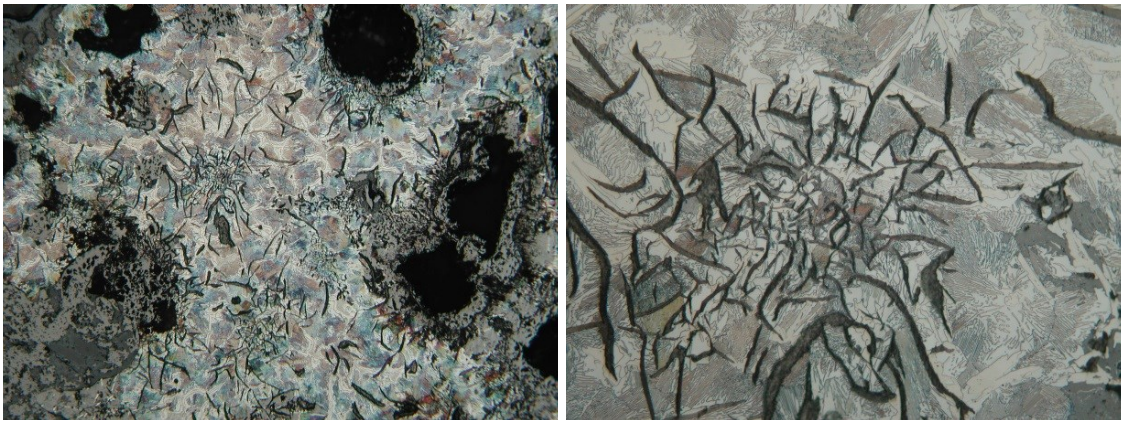
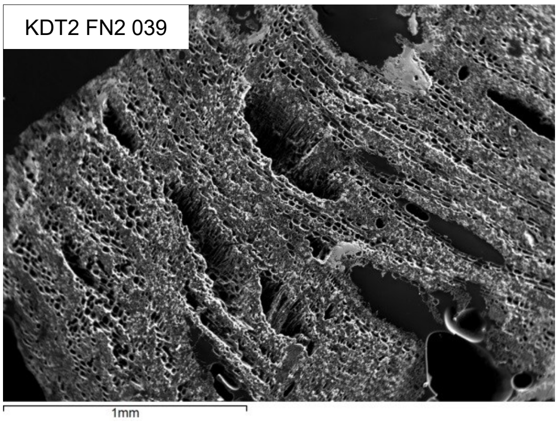


Figure 8.59 Etched grey cast iron prill found previously in one of the KDT2 slag (Venunan 2011). This etching was done specifically for this research. Image width ≈ 3.5 and 1.75 mm.

In addition to the phosphorous seen in white cast iron, SEM-EDS spot analyses of a phosphorous-rich phase (Figure 8.56) in various related samples infers that the contents range from 2-13 wt% P, whereas the "bulk" chemical analysis of large phosphoric iron areas determined phosphorous around 5-7 wt%. These high P contents likely exceed a range of this alloying element in ancient and experimental iron products (approximately 0.05-2%) (McDonnell 1989, 375; Pleiner 2000, 2006; Rostoker and Bronson 1990, 22, 111-112; Salter and Crew 1997). Despite low contents of phosphorous in both laterite (0.2-0.9 wt%) and slag (0.2-0.3 wt%), phosphorous was enriched and concentrated in iron, similar to what Salter and Crew (1997) discussed in their experiment; however, phosphoric iron in this research contains much higher phosphorous levels. The effect of phosphorous in iron is to increase the hardness of iron and steels, but at the same time, also make iron more brittle. When hot, phosphorous-rich iron can be easy to forge like soft iron. On the other hand, this element in iron also inhibits carbon diffusion at high temperatures and also hamper solidification of cast iron, giving more time for casting. It is also known to enhance fluidity of liquid cast iron (as much as 7% P) (Buchwald 2005, 170-178, Rostoker and Bronson 1990, 22; Tylecote 1986, 144-145).

Although the evidence concerning metallic iron in slag present above seems to be consistent with carbon-rich iron, Low-carbon iron (soft iron) with ferritic structure was also identified among large iron fragments, but the photomicrographs taken were not of acceptable quality. The existence of low and high-carbon iron in slag is a clear evidence that iron produced in these furnaces would have a variety of carbon levels.

The characterisation of the slag microstructure ends with reference to residual inclusions of unreacted or only partly reacted materials, even though these are very rare. The most interesting inclusions are probable fragments of laterite and quartz-rich regions, in addition to rare charcoal fragments (Figure 8.60). Although the chemical analysis of charcoal was not employed, SEM-EDS spot and area analyses, though resulting in very low totals, determined only CaO along with Al_2O_3 and SiO_2.



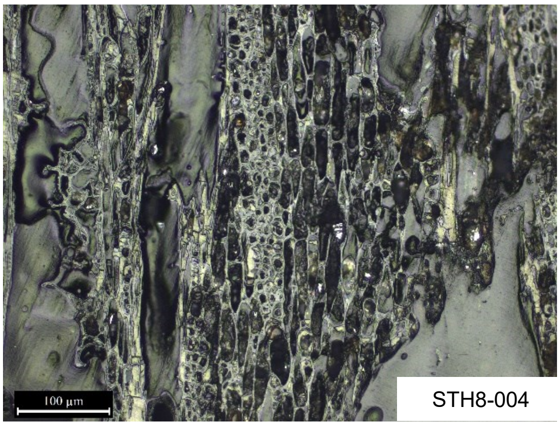


Figure 8.60 BSE image and micrograph show remains of charcoal embedded in slag.

Only two inclusions are found in two different samples, out of 63 slag samples examined, may be possibly described as the vestiges of laterite fragments, given their similarity to the archaeological laterite samples (Figure 8.61). Macrostructurally, the inclusion in STH8T1-195 resembles the nodular shape seen in the KDT2 samples (Figure 8.7). Its microstructure is dominated by the iron-rich white phase. In contrast, the inclusion in KDT3-004 looks quite similar macrostructurally to the fragments of laterite from STH8 and is obviously distinguishable from the surrounding quartz region. The chemical composition of the inclusion in STH8, analysed by SEM-EDS, is comparable to those of the laterites characterised before, most notably in the high level of alumina (Figure 8.62).

While it is reasonable to think that these small rock fragments are remnants of the ore, it should be acknowledged that they may also have entered the system with clay or sand, deliberately or not, given the widespread abundance of laterite in the local geology (see section 6.2).

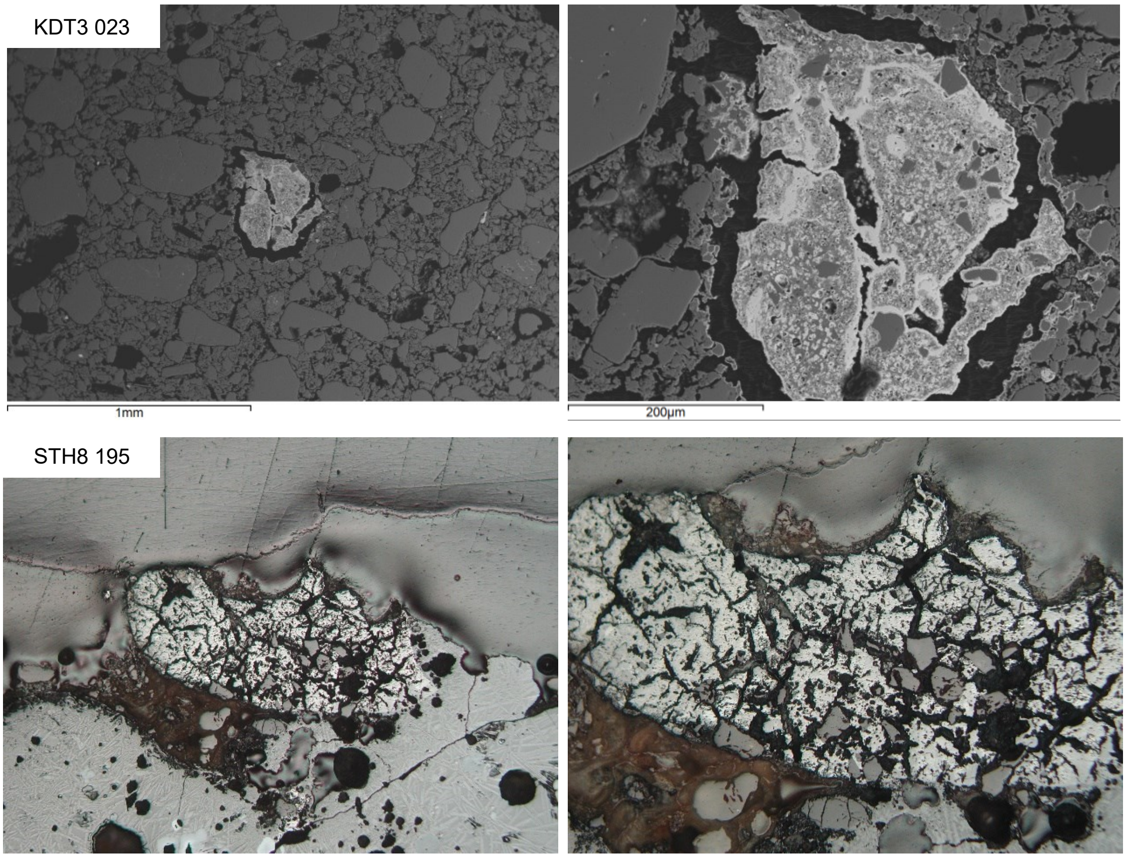
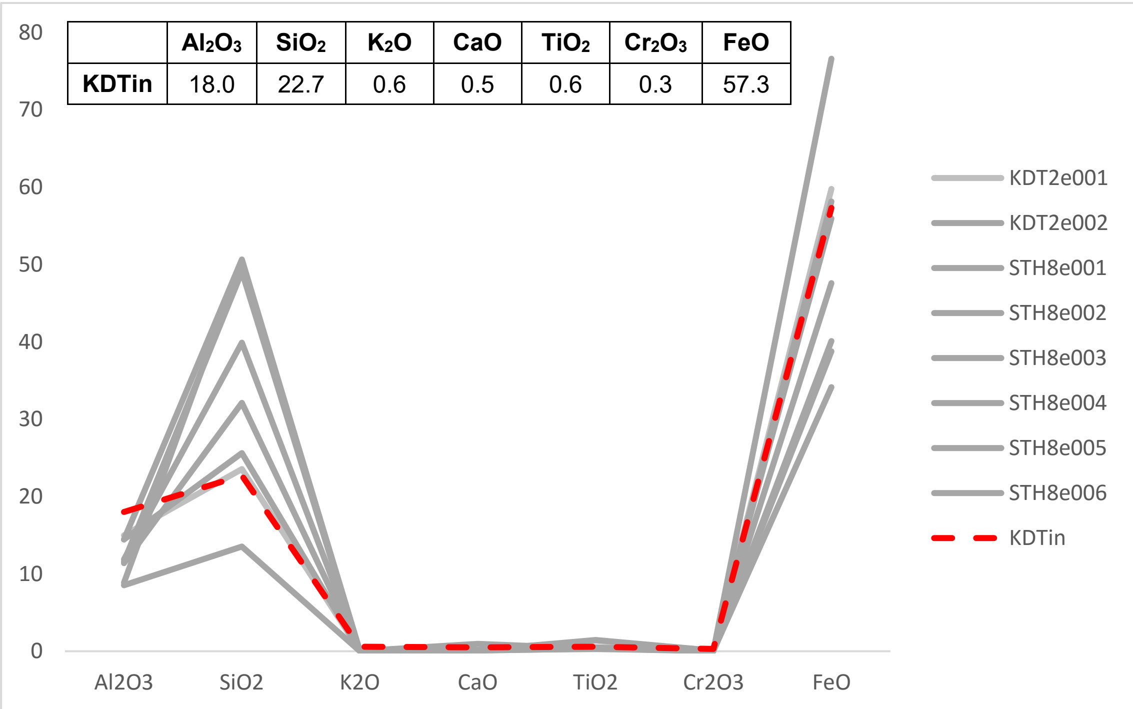


Figure 8.61 Possible vestiges of laterite fragments remaining in slag (Image width ≈ 3.5mm)



	Al_2O_3	SiO_2	K_2O	CaO	TiO_2	Cr_2O_3	FeO
KDTin	18.0	22.7	0.6	0.5	0.6	0.3	57.3

Figure 8.62 Line plots show a chemical comparison between various laterite samples and “laterite” inclusion in KDT3 023 (dashed red line). Chemical composition of the KDT3 023 “laterite” inclusion, obtained by the area analysis using SEM-EDS. Data are averaged and normalised to 100%. Original totals are 96-101wt%.

Last, quartz-rich regions were observed in some of the partially porous and or more substantially porous slag samples. These residual inclusions are internally shattered and partly dissolved in the matrix (Figure 8.63 and 8.64). Iron particles are often seen trapped inside these regions of slag, possibly due to their higher viscosity preventing iron globules to coalesce with others. There are minerals often seen recrystallising from these grains.

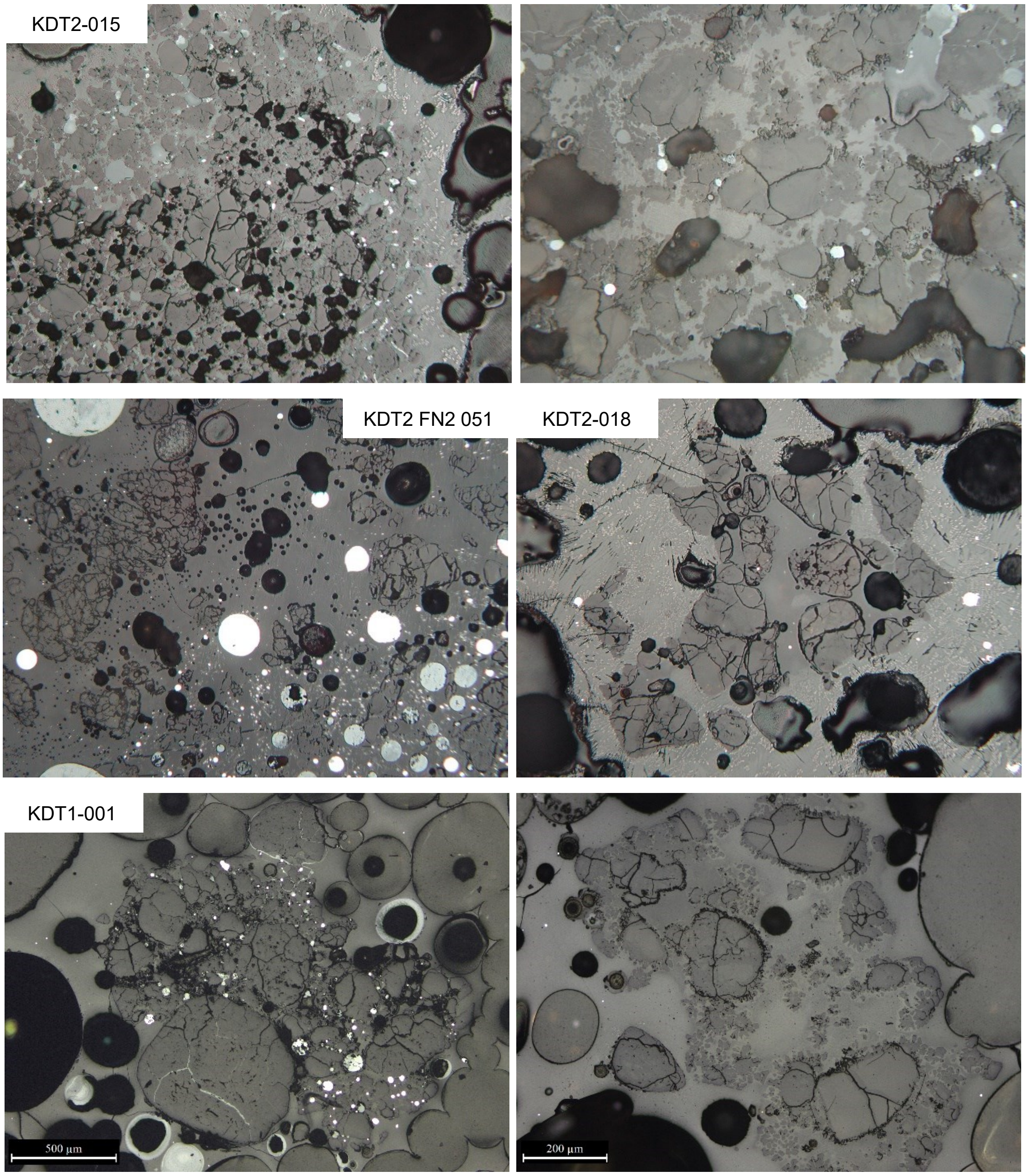


Figure 8.63 Micrographs show partly dissolved and cracked quartz grains (light grey) in slag structure

(Image width ≈ 3.5 mm (KDT2-015 left and KDT2 FN2 051) and 1.75mm (KDT2-015 right and KDT2-018))

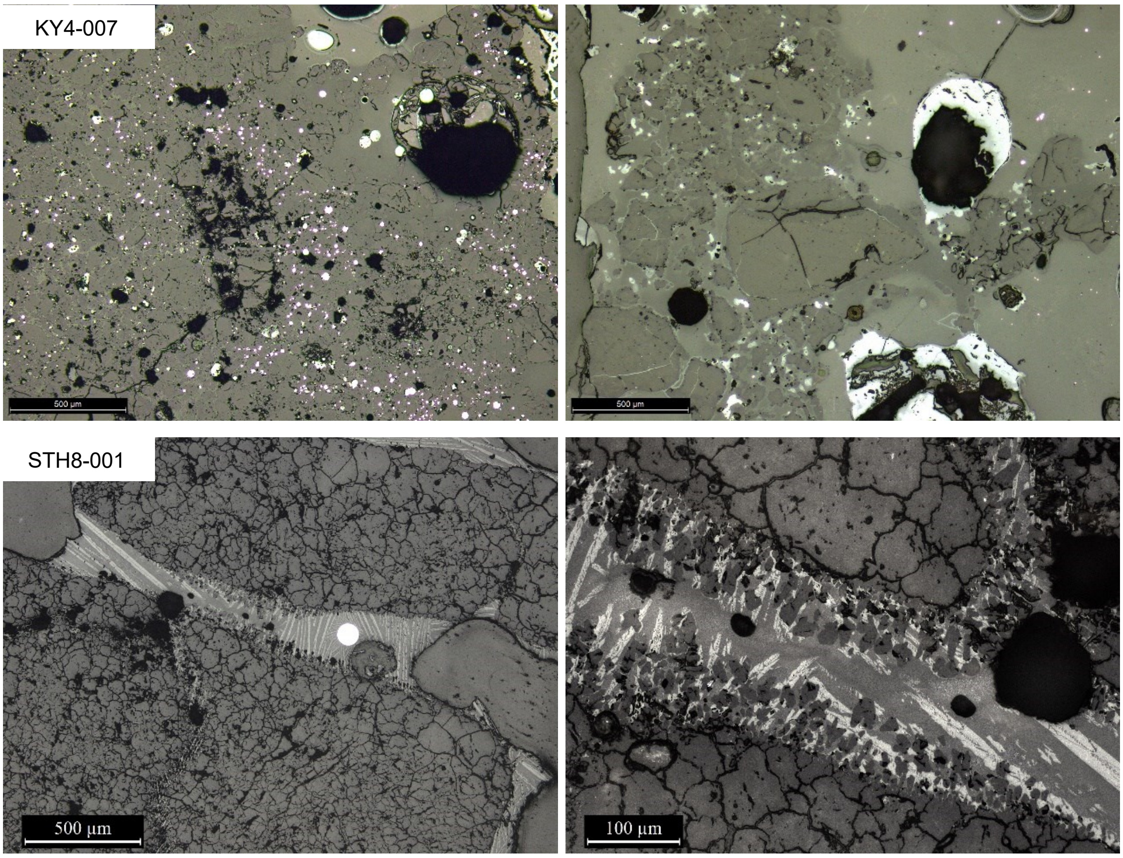


Figure 8.64 More examples of quartz grains in slag structure

These partly reacted quartz grains clearly denote the contribution of quartz into the slag chemistry; however, again their origins had to be confirmed. As discussed above, both technical ceramics and laterite carry quartz in their structure and are potential candidates for contributing quartz to the slag formation. Considering the presence of iron within these grains, there is a possibility that the grains may have been once residual chucks of complex rocks, possibly quartz-rich ore. Accordingly, iron was likely to form within these grains and was trapped as quartz was not completely molten into slag.

8.3.3.1.1.2 Chemical compositional characterisation

The WD-XRF results of 109 slag samples, summarised in Table 8.11-8.12 and reported in full in Appendices H and J, are consistent with the observations made above. As expected, silica, iron oxide, and alumina as the main constituent compounds. Compared to typical smelting slag (Tylecote 1987; Pleiner 2000; Paynter 2006), it is noticeable that silica and iron oxide are noticeably low (less than 40 wt% and 50 wt% respectively), while alumina is significantly high (13-15 wt%). When the three major oxides are plotted into the ternary diagram of corresponding system, they form a relatively tight cluster around the low iron eutectic (the so-called optimum 1, cf. Charlton *et al*. 2010; Rehren *et al*. 2007), spreading into the alumina-rich region, with no discernible subgroups. Distribution patterns can be observed by plotting the samples into the same diagram by their macrostructural subgroups (Figure 8.65-8.67). Dense and semi-porous groups tend to spread within the same areas; although, the latter group is seen to disperse into iron-rich and silica-rich regions, possibly explained by a higher chemical variation than other groups. In contrast to the first two groups, the porous slag, due to having the highest contents of silica and least iron oxide levels, moves toward a silica-rich region.

In terms of other oxides (Figure 8.69), chemical variations can be observed for the oxides associated with fuel ash (P_2O_5, K_2O, and CaO) as well as MnO. In addition to these oxides, P_2O_5 appears to be similar to what reported in the ore and technical ceramic samples. K_2O and CaO are higher than in both components aforementioned, thus likely to be derived from fuel burned. V_2O_5, Cr_2O_3, CuO, ZnO, Rb_2O, SrO, and ZrO_2 seem to be relatively comparable between the slag deposits. TiO_2 is of most interesting as it divides slag clusters into two subgroups (eastern (KY, NC, KSK, KDT, BKT) and western groups (STH groups)) which were already proposed by the size and weight data (see section 7.3.2.1 and Figure 7.77). Multivariate statistical analysis in section 8.4.1.4 may further help validate these groups observed.

Together with the lack of between-site variability noted in the microstructure, this indicates that all slag samples derive from the same technical practice or very similar traditions (Figure 8.65). A more detailed exploration of these findings, presented in section 8.4.1, may help elucidate variability and how slag was formed and influenced by different smelting components, but the overall pattern is one of uniformity across the dataset.

Overall, the analysis of the slag lumps confirms that they derive from bloomery iron smelting. While there is variation in the amount of porosity, the solid part of the slag is very similar across the assemblage, characterised by relatively high alumina and low iron levels, and corresponding with microstructures that lack any free iron oxide. The slag is generally very well reacted, with very few residual inclusions left, and there are no major differences between sites.

wt%	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**TiO_2**	**V_2O_5**	**Cr_2O_3**	**MnO**	**FeO**	*F-Values*	RII%
KY4 (n=7)	14.53	35.23	0.24	0.53	1.44	1.02	0.16	0.11	1.03	45.30	2.4	1.8
Min	13.33	32.78	0.19	0.41	0.53	0.75	0.14	0.1	0.53	42.39	2.2	1.6
Max	15.55	37.55	0.34	0.74	2.18	1.12	0.19	0.13	2.61	49.48	2.7	2.1
STD	0.9	1.6	0.0	0.1	0.6	0.1	0.0	0.0	0.7	2.4	0.2	0.2
CV	6	5	20	20	44	13	9	11	71	5	7	9
NC4 (n=7)	15.01	36.22	0.26	0.62	1.69	1.13	0.18	0.12	1.05	43.32	2.4	2.0
Min	14.14	32.06	0.18	0.47	1.40	0.89	0.16	0.11	0.25	38.62	2.2	1.6
Max	16.31	38.71	0.44	0.81	1.97	1.38	0.23	0.14	2.16	48.66	2.7	1.9
STD	0.8	2.6	0.1	0.1	0.2	0.2	0.0	0.0	0.8	3.2	0.2	0.2
CV	5	7	34	21	11	15	13	9	72	7	9	13
KSK1 (n=7)	15.80	37.87	0.27	0.50	1.29	1.23	0.19	0.13	1.12	41.19	2.4	2.2
Min	14.22	35.21	0.14	0.38	0.4	0.95	0.16	0.1	0.72	36.8	1.8	1.8
Max	16.98	42.7	0.36	0.8	2.51	1.44	0.21	0.16	1.62	43.81	2.6	2.6
STD	1.0	2.6	0.1	0.2	0.7	0.2	0.0	0.0	0.3	3.3	0.3	0.3
CV	6	7	26	34	57	16	10	20	30	8	14	14
KDT1 (n=5)	15.76	36.36	0.36	0.49	1.93	1.73	0.18	0.10	0.39	42.53	2.3	2.1
Min	14.19	33.13	0.24	0.31	0.29	1.38	0.17	0.09	0.21	33.48	2.1	1.6
Max	17.73	40.82	0.4	0.58	4.42	2.02	0.2	0.12	0.59	48.81	2.5	2.9
STD	1.4	2.9	0.1	0.1	1.6	0.3	0.0	0.0	0.1	5.6	0.1	0.5
CV	9	8	18	24	85	17	9	11	32	13	6	23
KDT2 (n=47)	14.53	33.94	0.41	0.43	1.04	1.57	0.19	0.11	0.45	47.12	2.3	1.7
Min	13.04	29	0.12	0.24	0.32	0.57	0.13	0.06	0.14	40.41	1.9	1.4
Max	16.88	43.24	0.63	0.68	2.42	1.96	0.25	0.15	1.37	56.17	3.2	2.6
STD	1.1	3.5	0.2	0.1	0.6	0.3	0.0	0.0	0.3	3.8	0.3	0.3
CV	8	10	53	27	54	20	14	23	59	8	11	18

Table 8.9 Mean WD-XRF data for the slag samples of each chosen slag deposit. *F*-values (the ratio of SiO_2 and Al_2O_3) and RII values (Reducible Iron Index), which helps track changes in the ore and furnace operation, respectively (Charlton *et al.* 2010, 356), are given here in order to facilitate arguments about the efficiency of reduction in Ban Kruat smelting operation later in this chapter. See the full WD-XRF data of each site analysed in Appendix H.

wt%	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**TiO_2**	**V_2O_5**	**Cr_2O_3**	**MnO**	**FeO**	*F*-values	RII%
KDT3 (n=5)	15.01	38.98	0.34	0.66	1.57	1.20	0.18	0.12	0.88	40.73	2.6	2.3
Min	14.35	36.39	0.21	0.48	1.12	1.11	0.16	0.08	0.66	65.34	2.3	2.0
Max	15.71	43.36	0.51	0.94	2.14	1.28	0.19	0.16	1.34	42.69	2.8	2.9
STD	0.6	2.7	0.1	0.2	0.4	0.1	0.0	0.0	0.3	3.1	0.2	0.4
CV	4	7	37	29	27	6	7	26	30	8	8	16
BKT5 (n=7)	14.51	36.09	0.29	0.53	1.13	1.04	0.17	0.12	1.04	44.71	2.5	1.9
Min	12.68	31.84	0.13	0.13	0.37	0.95	0.13	0.08	0.56	37.62	2.2	1.5
Max	15.78	42.5	0.69	0.69	0.8	1.36	0.2	0.16	2.37	50.97	3.0	2.5
STD	1.0	4.2	0.2	0.2	0.2	0.2	0.0	0.0	0.7	5.0	0.3	0.4
CV	7	12	64	29	20	23	14	25	65	11	12	22
STH8 M1 (n=7)	14.09	38.37	0.16	0.52	1.18	0.44	0.19	0.08	0.42	44.35	2.7	2.1
Min	13.38	33.45	0.08	0.33	0.6	0.37	0.16	0.07	0.06	44.56	2.5	1.6
Max	15.23	38.31	0.13	0.6	2.25	0.65	0.25	0.1	0.36	49.93	2.9	2.0
STD	0.7	3.0	0.1	0.1	0.7	0.0	0.0	0.0	0.4	4.0	0.2	0.3
CV	5	8	43	25	55	8	25	40	98	9	7	17
STH8/2 M6 (n=7)	14.22	36.38	0.09	0.46	1.08	0.43	0.20	0.08	0.13	46.81	2.6	1.9
Min	13.38	33.45	0.08	0.33	0.6	0.37	0.16	0.06	0.05	44.56	2.5	1.6
Max	15.23	38.31	0.13	0.6	2.25	0.65	0.25	0.1	0.36	49.93	2.8	2.0
STD	0.6	1.9	0.0	0.1	0.7	0.1	0.0	0.0	0.1	2.1	0.1	0.2
CV	4	5	19	18	61	24	17	18	84	4	5	9
STH10 S (n=7)	13.30	36.05	0.09	0.32	0.42	0.45	0.22	0.06	0.07	48.93	2.7	1.8
Min	11.39	34.26	0.07	0.21	0.24	0.39	0.19	0.05	0.05	47.21	2.4	1.4
Max	14.41	39.83	0.2	0.41	0.72	0.48	0.23	0.07	0.1	54.44	3.3	2.1
STD	1.1	2.6	0.0	0.1	0.2	0.0	0.0	0.0	0.0	2.8	0.3	0.2
CV	8	7	51	19	41	8	8	13	23	6	12	12

Table 8.10 Mean WD-XRF data for the slag samples of each chosen slag deposit (continued)

ppm	**CuO**	**ZnO**	**Rb_2O**	**SrO**	**ZrO_2**	**BaO**	**La_2O_3**	**CeO_2**	**Nd_2O_3**
KY4 (n=7)	35	60	42	84	600	2618	-	483	-
Min	5	25	33	31	573	1383	25	330	63
Max	128	107	51	145	656	7234	56	868	-
SD	46.1	31.0	7.8	39.7	36.6	2134.2	-	183.1	-
CV	133	51	18	47	6	82	-	38	-
NC4 (n=7)	64	70	36	122	608	2679	-	514	-
Min	5	13	20	98	486	433	28	192	7
Max	96	104	48	161	659	6540	60	1019	41
SD	31.8	39.8	8.7	25.5	58.0	2209.6	-	329.2	-
CV	49	57	24	21	10	82	-	64	-
KSK1 (n=7)	53	75	36	101	636	2505	18	609	-
Min	2	39	25	34	571	1752	8	514	5
Max	91	104	48	138	694	3493	44	937	-
SD	39.3	24.0	9.1	61.3	49.3	723.6	14.3	185.7	-
CV	74	32	25	61	8	29	78	31	-
KDT1 (n=5)	64	84	39	124	578	713	30	110	-
Min	28	39	30	25	491	331	1	13	24
Max	85	122	49	293	669	1055	88	300	25
SD	24.3	32.9	7.5	107.8	65.6	288.9	36.1	130.0	-
CV	38	39	19	87	11	41	122	118	-
KDT2 (n=47)	73	88	36	73	577	838	-	255	-
Min	14	15	18	27	476	221	2	6	1
Max	129	148	77	232	722	1884	85	574	141
SD	37.2	32.7	11.3	46.4	76.0	514.7	-	171.4	-
CV	51	37	31	63	13	61	-	67	-
KDT3 (n=5)	60	74	39	88	547	1875	25	526	-
Min	24	25	23	47	510	1476	18	428	1
Max	110	118	65	108	609	2599	38	806	19
SD	36.4	36.8	16.9	25.7	38.0	446.5	9.5	181.7	-
CV	61	50	43	29	7	24	37	35	-

Table 8.11 Mean WD-XRF data for the slag samples of each chosen slag deposit (continued). Nd_2O_3 was detected in less than half of the sample population of each slag site, thus not calculated for average, SD, and CV.

ppm	**CuO**	**ZnO**	**Rb_2O**	**SrO**	**ZrO_2**	**BaO**	**La_2O_3**	**CeO_2**	**Nd_2O_3**
BKT5 (n=7)	68	99	45	63	601	2317	37	541	-
Min	6	33	34	45	536	990	4	310	4
Max	124	177	56	79	721	5318	77	1122	25
SD	53.7	48.5	9.5	12.3	62.2	1498.9	30.5	281.3	-
CV	78	49	21	20	10	65	82	52	-
STH8 M1 (n=7)	87	71	46	45	567	828	-	349	-
Min	69	25	29	26	339	78	-	72	31
Max	150	94	66	73	523	800	-	265	80
SD	19.2	20.0	17.4	22.2	131.8	747.9	-	308.9	-
CV	22	28	37	50	23	90	-	89	-
STH8/2 M6 (n=7)	113	61	46	44	401	314	-	123	-
Min	69	25	29	26	339	78	-	56	18
Max	150	94	66	73	523	800	-	265	42
SD	31.2	28.2	14.5	16.3	61.8	248.3	-	84.9	-
CV	28	46	32	37	15	79	-	69	-
STH10 S (n=7)	57	48	20	18	536	219	24	80	-
Min	12	13	12	11	450	132	3	25	-
Max	114	96	33	27	670	388	56	151	-
SD	44.2	36.7	7.2	6.0	96.6	84.4	25.7	45.3	-
CV	77	77	36	34	18	39	105	57	-

Table 8.12 Mean WD-XRF data for the slag samples of each chosen slag deposit (continued).

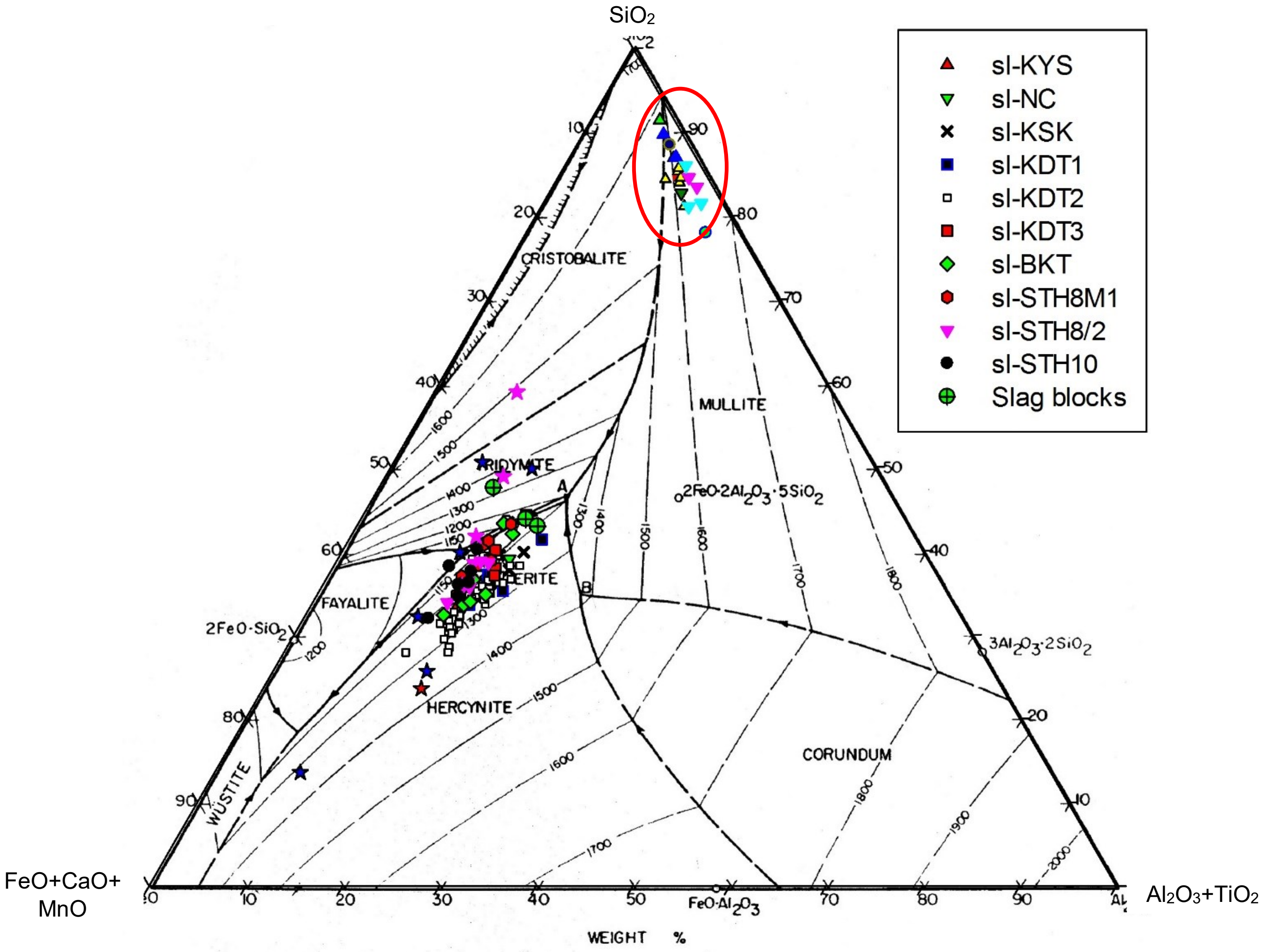


Figure 8.65 FeO(+CaO+MnO)- SiO_2-Al_2O_3(+TiO_2) ternary diagram with all amorphous slag plotted. Laterite (stars) and technical ceramics (marked by red circle) are also shown.

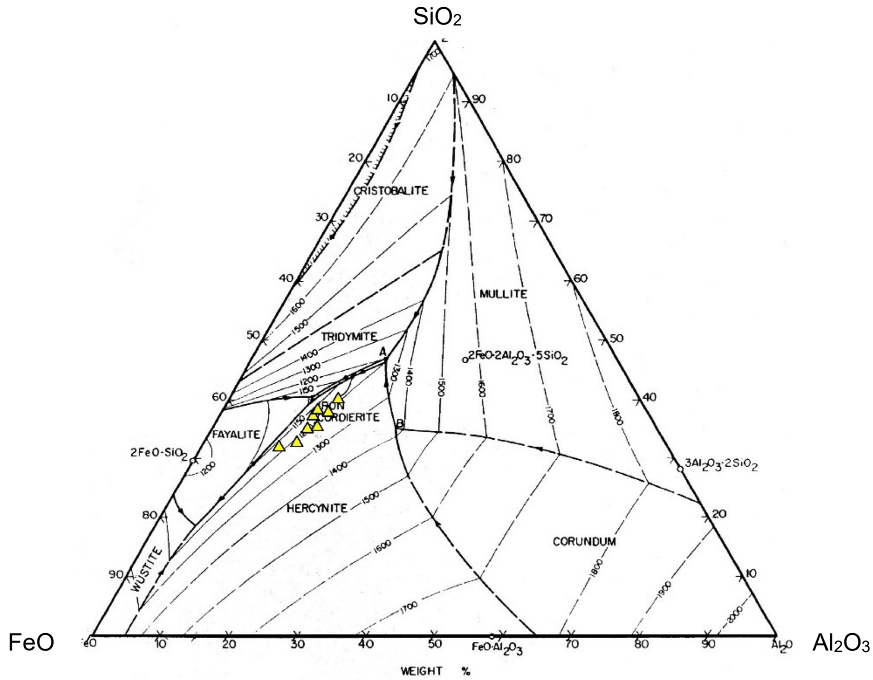


Figure 8.66 FeO-SiO_2-Al_2O_3 ternary diagram with only dense slag plotted. Only slag samples categorised macro- and microstructurally are included. The following two figures are produced following the same way.

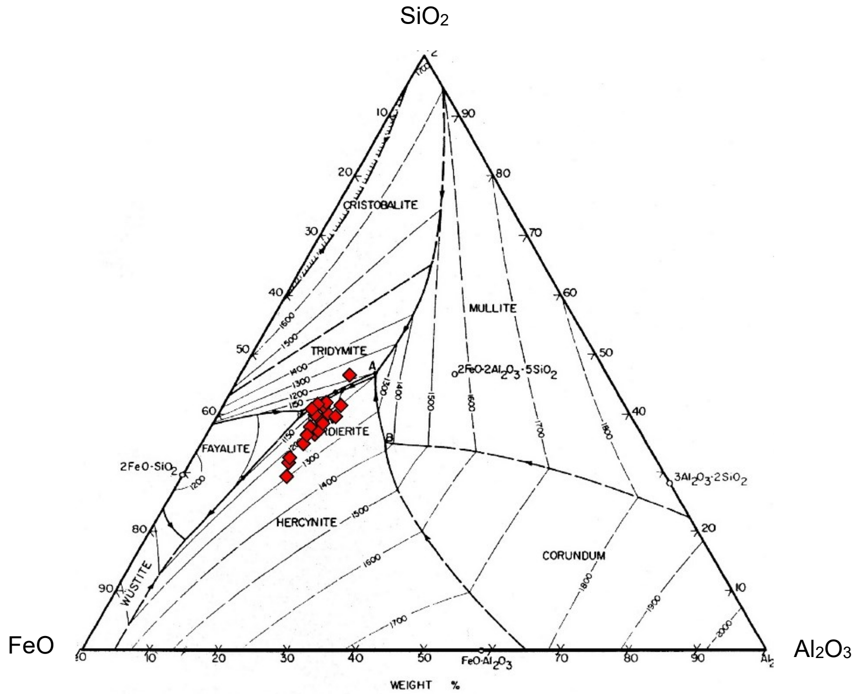


Figure 8.67 FeO-SiO_2-Al_2O_3 ternary diagram with only semi-porous slag plotted.

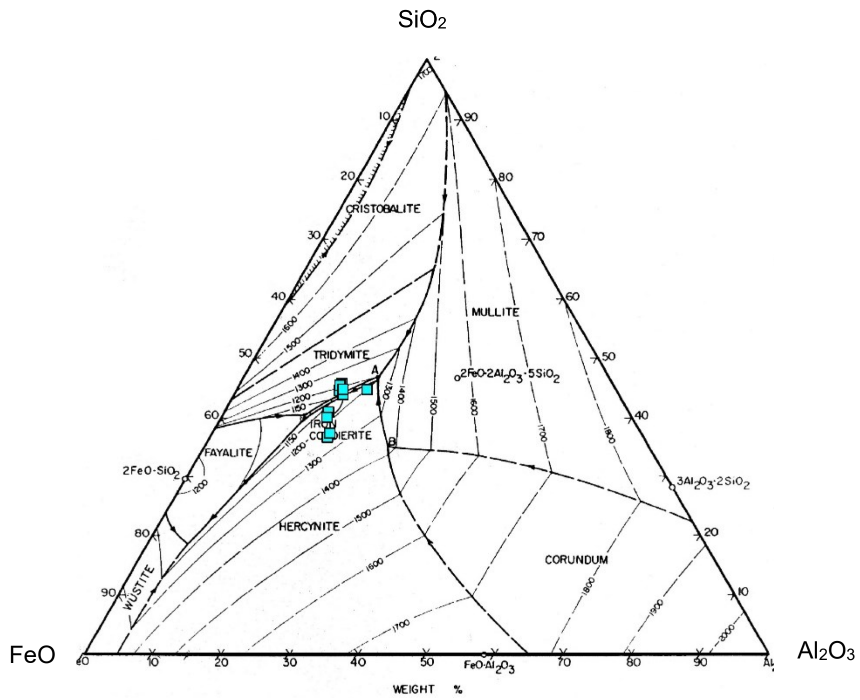
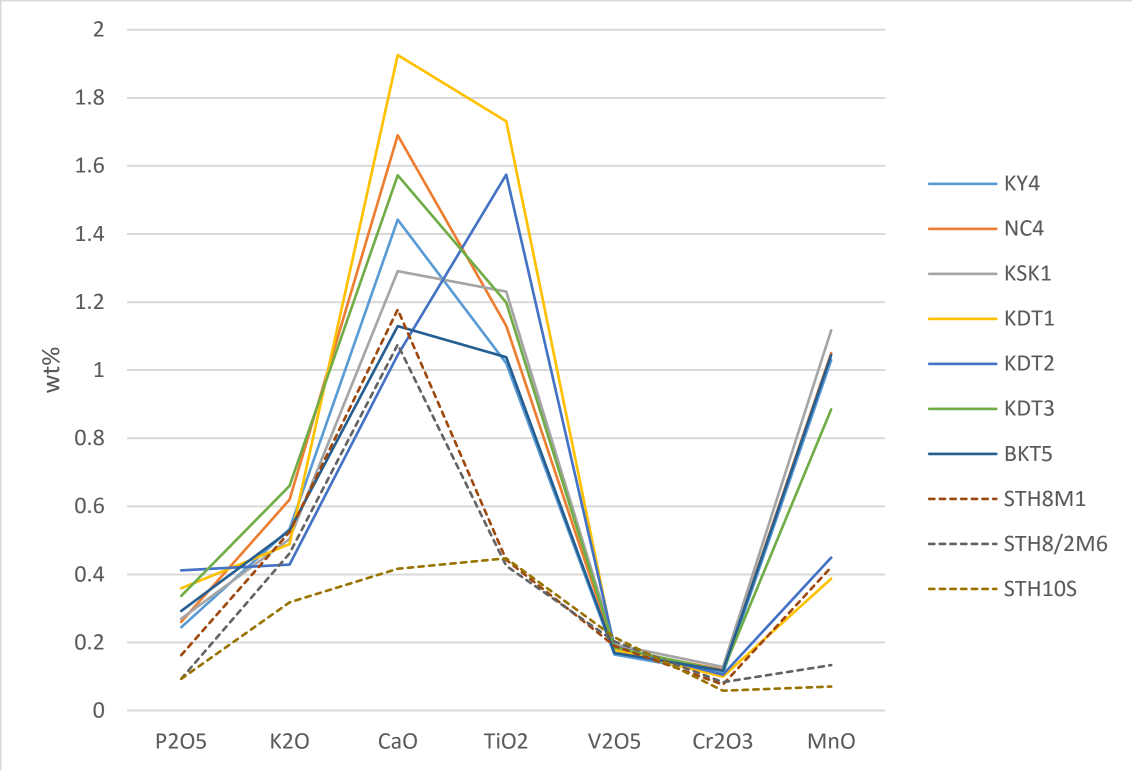


Figure 8.68 FeO-SiO_2-Al_2O_3 ternary diagram with only porous slag plotted.



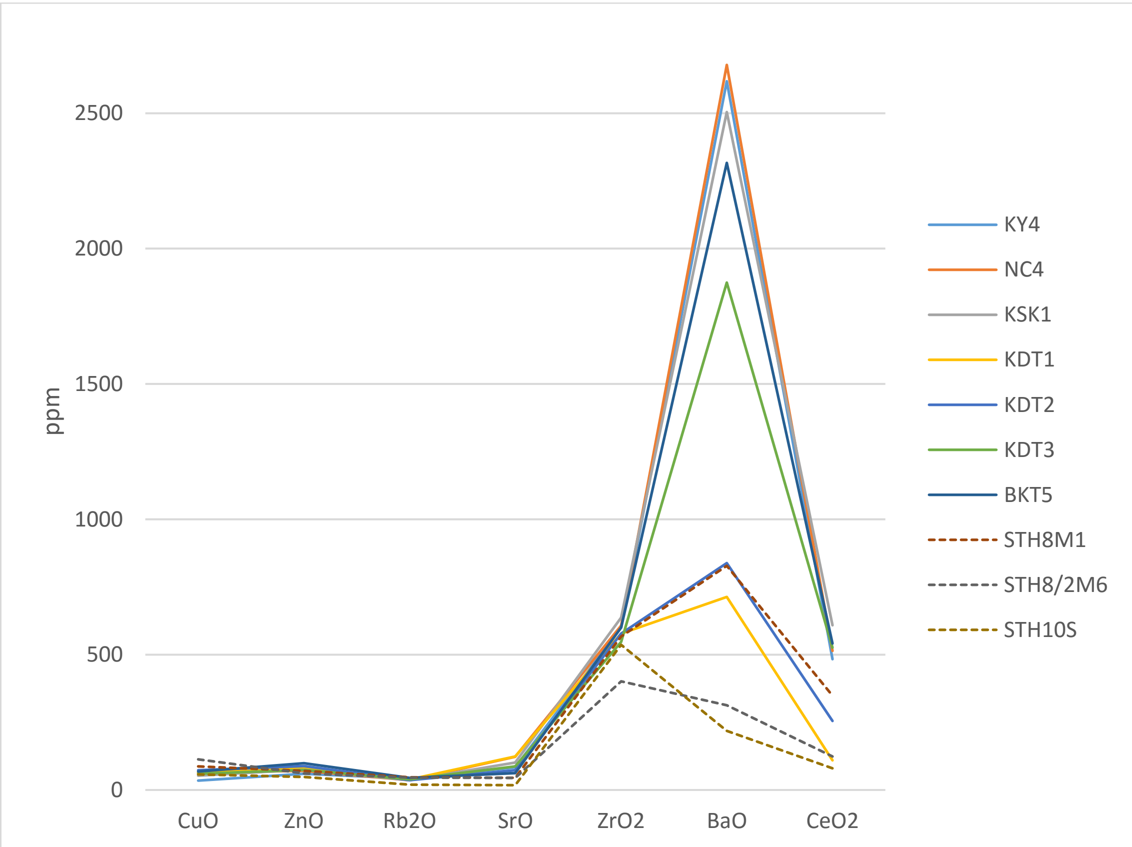


Figure 8.69 Line plot shows a comparison of minor and trace oxides in smelting slag collected from various slag clusters. Data are averaged and normalised to 100%.

8.3.3.1.2 Large slag blocks

The macroscopic inspection of the large slag blocks showed that their structure was heterogeneously formed of slag, quartz grains, and technical ceramic fragments fused together in multiple layers to form slag-like material, likely caused by an incomplete reduction process (see section 7.3.2.1). As mentioned, one fragment from each block (three samples in total) was analysed. It should be noted that a single sample of such heterogeneous blocks is only representative to a limited extent (see Humphris 2009; Iles 2011 for the systematic studies of slag blocks and a discussion about the nature of slag blocks).

Compared to the more common smelting slag above, their cross-sections resemble those of the semi-porous slag group, only larger grain-sized and more heterogeneous as various inclusions and discernible areas can be seen (Figure 8.70).

Figure 8.70 Cross-sections of slag block samples (slb-NC – top left, slb-KDT2TP2 – top right, and slb-STH8/2M4 - below)

Microstructurally, the main phases are the same as those seen previously in typical smelting slag, but their size and shape of olivine crystals are considerably different with the exception of hercynite that is identical. The olivine phases are not predominantly elongated as seen previously, but often blockier and more irregular in distribution. Unlike the rare and localised occurrence in smelting slag lumps, quartz particles can be seen widely distributed across the structure of the large blocks. Many of them are cracked and appear to have reacted with the surrounding matrix to form new phases (e.g. fayalite and glassy matrix). In slb-NC (Figure 8.71), quartz grains have partly melted and bonded with alumina and calcium oxide, recrystallising in the form of anorthite ($CaAl_2Si_2O_8$) interlacing with fayalite and hercynite. Compared to slag lumps, the microstructures observed in these slag blocks are heterogeneous and not well reacted as many inclusions left in slag corresponding to their macrostructure that consists of slag, technical ceramics, and baked clay fragments. It is worth mentioning that the remains of ore minerals, similar to the inclusion in Figure 8.61, could not be found in these samples examined. However, one may argue that these quartz grains may be remainders of laterite ores smelted (see Figure 8.63 and discussion on laterite samples in section 8.3.1). Metallic iron was only observed in slb-NC, where a few iron particles appear to be in the process of coalescing together into larger globules.

Their bulk chemical compositions of these blocks (Table 8.13), compared to the smelting slag lumps from the same sites (Figure 8.74), indicate that Al_2O_3 and SiO_2 are slightly higher, while FeO is lower, as illustrated by the ternary diagram of the same oxides. The other oxides are broadly comparable to their associated smelting slag, although with the notable difference that these slag block fragments contain higher CaO. Since both laterite and technical ceramics were shown to be low in this oxide, fuel ashes are presumably the main contributor of lime to the formation of slag. The calcium-rich nature of this material would have encouraged the formation of anorthite.

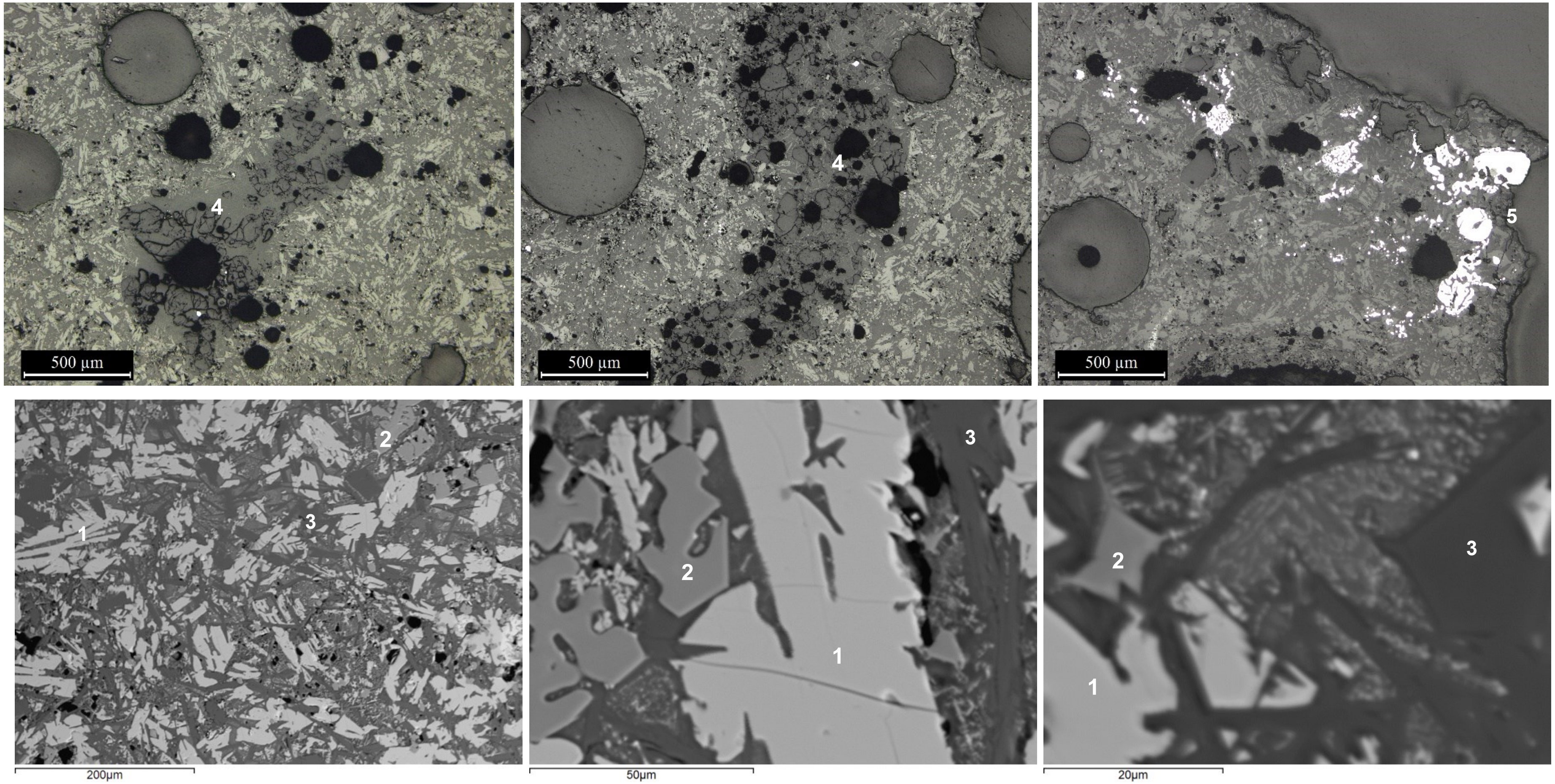


Figure 8.71 Microstructure of slb-NC which is dominated by fayalite (1), hercynite (2), anorthite (3), unreacted and reacted quartz particles (4), and iron metals (5).

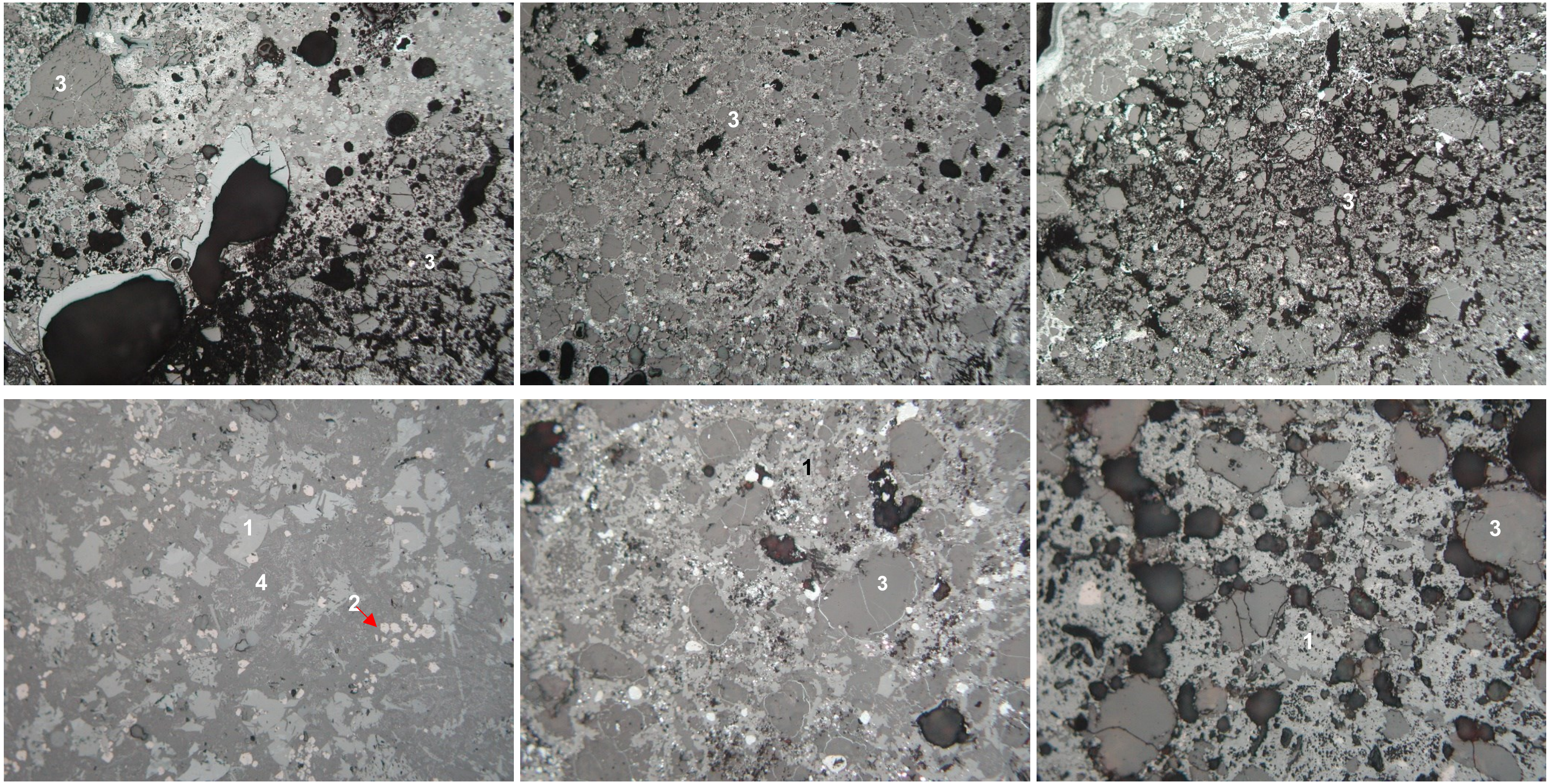


Figure 8.72 Microstructure of slb-KDT2TP2 show different phases, such as phases present including fayalite (1), FeO-TiO_2-Al_2O_3-rich phase (2), unreacted and reacted quartz particles (3), and glassy matrix (4). Image width – 3.5mm for top row and 0.85mm for lower row

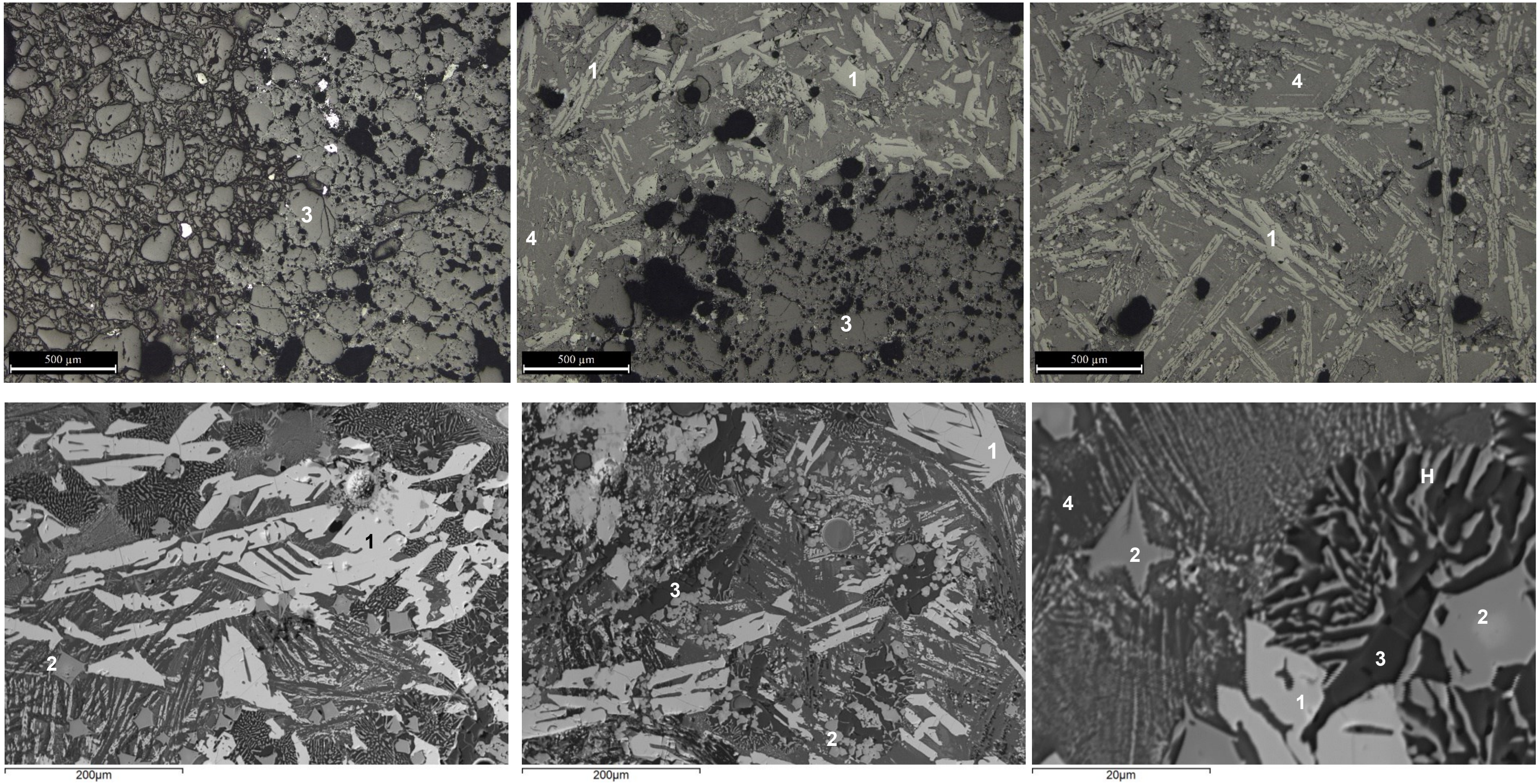


Figure 8.73 Microstructure of slb-STH8/2M4 illustrates phases present including fayalite (1), hercynite (2), unreacted and reacted quartz particles (3), and glassy matrix (4).

wt%	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	RII
slb-NC	15.75	42.97	0.42	0.85	3.29	1.00	0.16	0.08	0.66	34.55	2.9
slb-KDT2TP2	16.92	42.21	0.58	0.60	4.07	1.51	0.15	0.10	0.19	33.51	3.0
slb-STH8/2M4	11.30	46.99	0.17	0.44	1.19	0.45	0.19	0.11	0.10	38.93	2.9

ppm	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3
slb-NC	bdl	13	38	164	543	1526	bdl	420	bdl
slb-KDT2TP2	111	68	39	243	504	384	bdl	168	33
slb-STH8/2M4	186	45	41	58	455	275	9	120	2

Table 8.13 WD-XRF chemical data for selected oxides in slag block samples, normalised to 100%

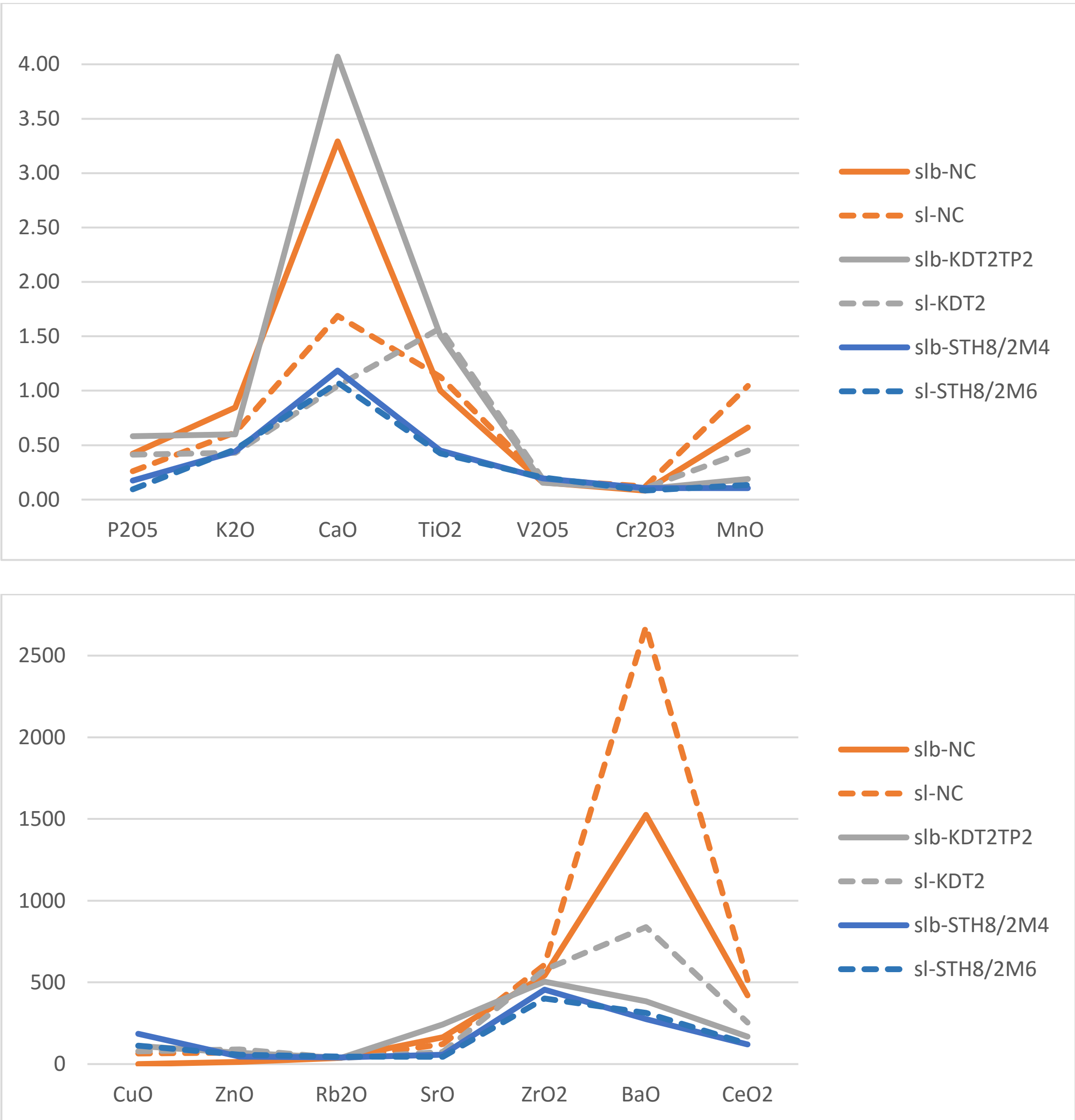


Figure 8.74 Line plots show an averaged chemical comparison of selected oxides between the slag block (slb-XX/solid line) and slag sample (sl-XX/dashed line).

Based on the findings, these slag blocks can arguably be described as incompletely reduced material, probably from failed smelt operations. As the smelt failed, slag formed along with technical ceramics and possibly ore fragments, assuming the quartz grains as remnants of laterite ores, could not further reduced and were fused into a large mass. Arguably, their structure would have become very similar to that of the more typical smelting slag lumps if the smelt was successful, and thus we can infer that the raw materials would have been broadly the same. Nonetheless, there are discrepancies concerning their origin and CaO contents between the slag blocks and slag lumps. The analyses characterised a CaO-rich nature of these blocks which chemically contrasts to the slag lumps which are likely to have derived from the same smelting system. This raises a question if one would argue for a charcoal-rich environment which promoted the formation of carbon-rich iron (e.g. prills and cast iron). This issue will be revisited again below when discussing the technical parameters in ironworking technologies in Ban Kruat.

While the sizes of the blocks from NC4 and KDT2 (approximately 48-88cm long, 39-78cm wide, and 35-40cm high) could have been accommodated by the reconstructed furnaces at KDT2 (60-80cm in diameter for their chamber sizes), the STH8/2 M4 blocks (150cm long, 110cm wide, and 130cm high) are much larger than the KDT2 furnaces; therefore, it can be speculated that larger furnaces which could accommodate these blocks can be expected.

8.3.3.2 Convex slag: a possible smithing slag

This section is devoted to the analyses that sought to test the initial interpretation of a group of metallurgical debris as smithing slag. Eighteen specimens (six from KDT2 and 12 from STH8 T1) from the particular contexts discussed in section 7.3.2.1 were selected for further examinations.

Macrostructurally, they are broadly convex in shape and comparatively denser, hence heavier than the amorphous smelting slag lumps of the same size (Figure 8.75) (see also section 7.3.2.1). The KDT2 samples predominantly have concave/convex shapes (with uneven top surfaces), while the STH8 ones mostly have flat/convex shape (Figure 8.76). Rounded pores can often be seen, probably from trapped gasses, but they are much scarcer than in smelting slag. Elongated or angular pores are also present, likely from poor consolidation during slag formation.

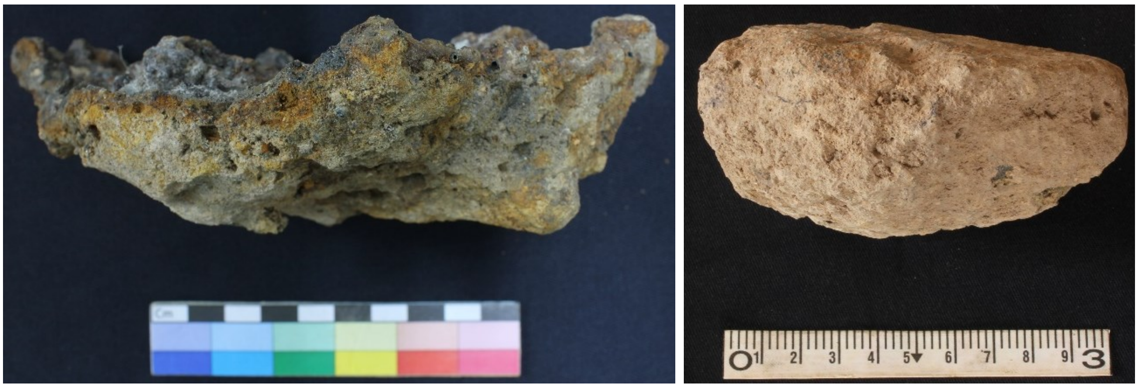


Figure 8.75 Examples of convex slag cakes (KDT2-left and STH8-right). More examples can be seen in Chapter 7.

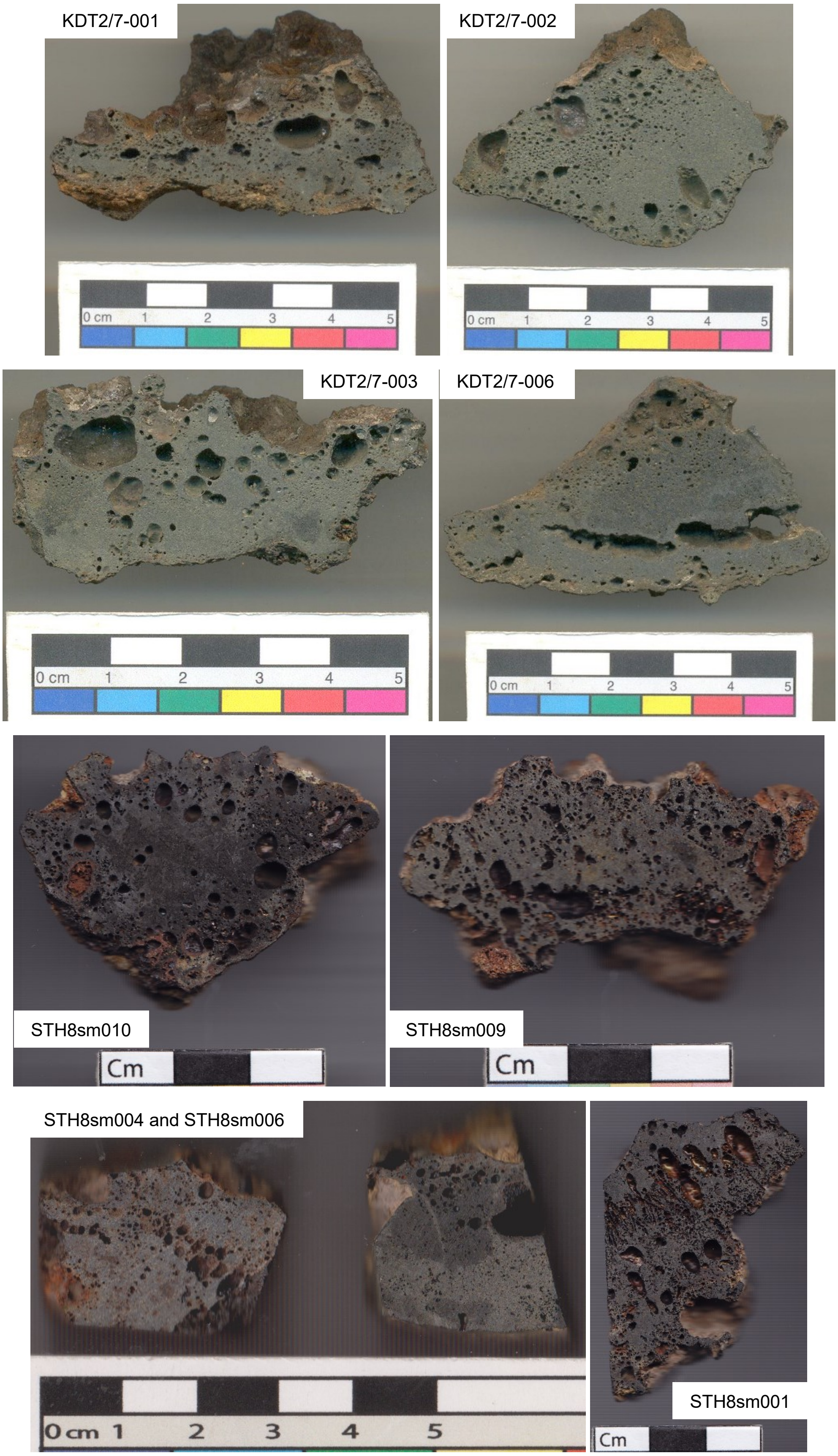


Figure 8.76 Examples of cross-sections of plano-convex shaped slag (four upper images-KDT2 and four lower images-STH8 T1)

Microstructural analysis further emphasises the differences between this slag and smelting slag, even though both groups share some phases, namely the dominant presence of fayalite and hercynite (Figure 8.77). Compared to smithing slag recovered elsewhere (cf. Serneels and Perret 2003), they are relatively homogeneous, but hammerscale flakes can be identified as the predominant residual inclusion; this is in contrast with smelting slag samples that generally have iron metals in many regions and rare quartz inclusions in some samples. Having said this, quartz inclusions can still be observed occasionally on the surface area of these cakes, possibly from the wall or hearth lining, as well as within the microstructure of some samples. A remnant fragment of charcoal was also noticed (Figure 8.82). Compared to smelting slag, fayalite is well-developed, blocky and euhedral rather than skeletal and elongated, while hercynite is rarer and appears smaller and often superimposing fayalite (Figure 8.77-8.79). In all cases, these two phases are comparatively larger, indicating a slow cooling rate. Besides the different sizes of common phases, the microanalysis also revealed the presence of free iron oxide and leucite ($K[AlSi_2O_6]$) which are phases exclusively found in this group of slag (Figure 8.78-8.80). Leucite is observed to grow out of the glassy matrix, which becomes hardly visible (Figure 8.83). The most common iron oxide phase is plausibly described as wüstite, based on its sub-rounded to rounded shape and chemical data obtained from SEM-EDS; however, some of them tend to occasionally have sub-angular shape, similar to spinel, and/or contain TiO_2.

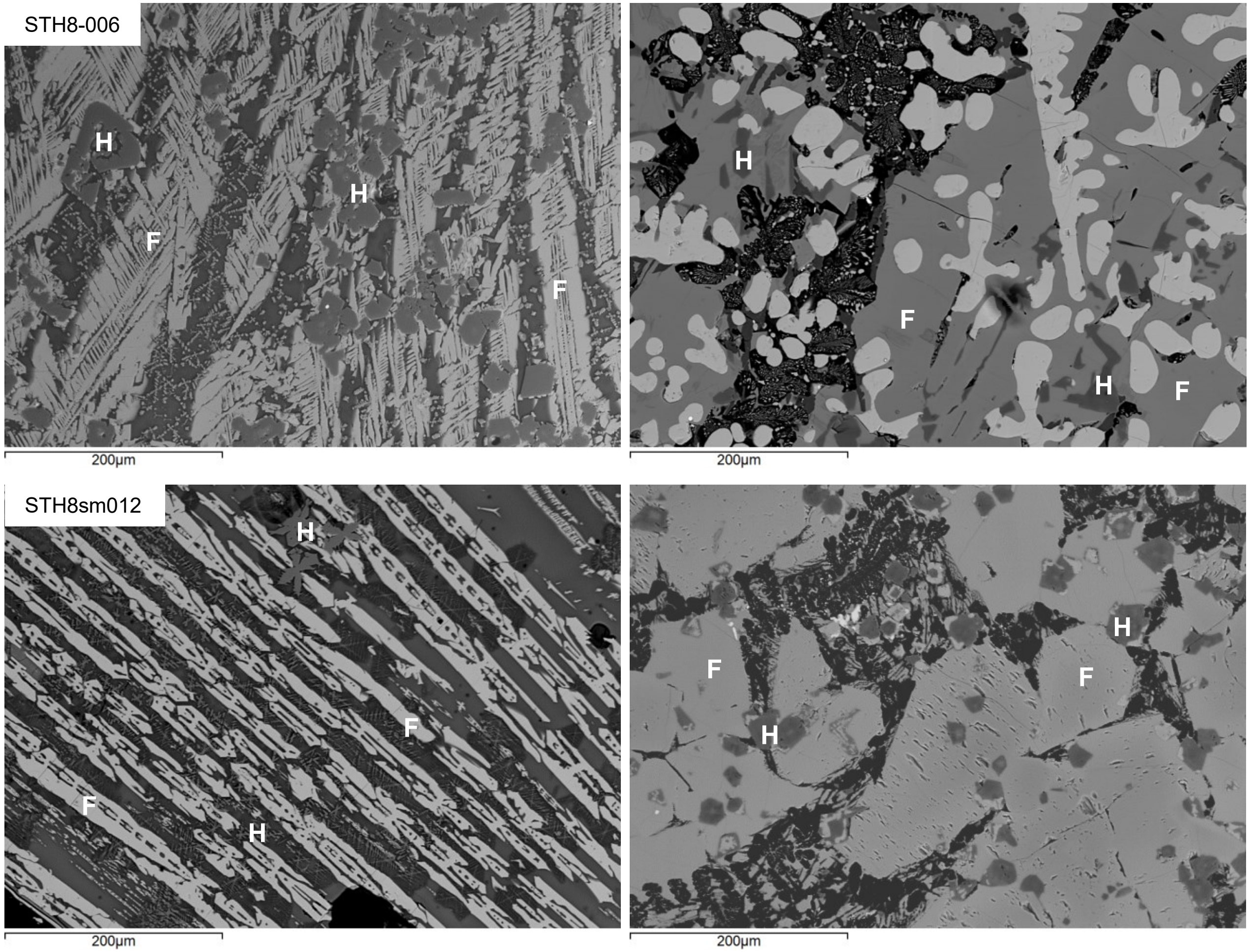


Figure 8.77 BSE images of the smelting slag (left images) in comparison to the smithing slag (right images) show shared phases, fayalite (F) and hercynite (H)

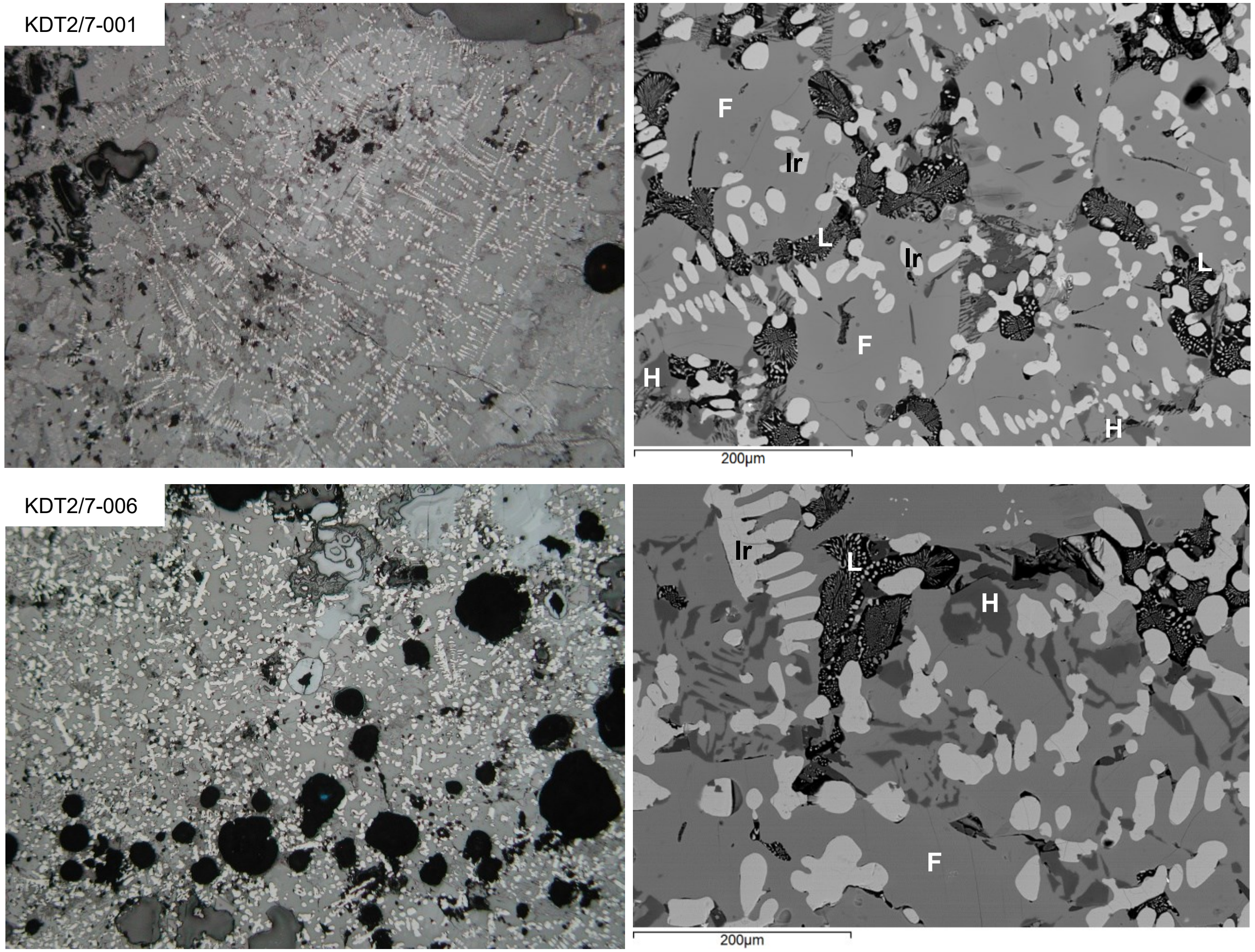


Figure 8.78 Examples of microstructure of convex shaped slag from KDT2 Furnace7 (KDT2/7). F-fayalite, H-hercynite, Ir-iron oxide, and L-leucite.

Image width ≈ 3.5mm

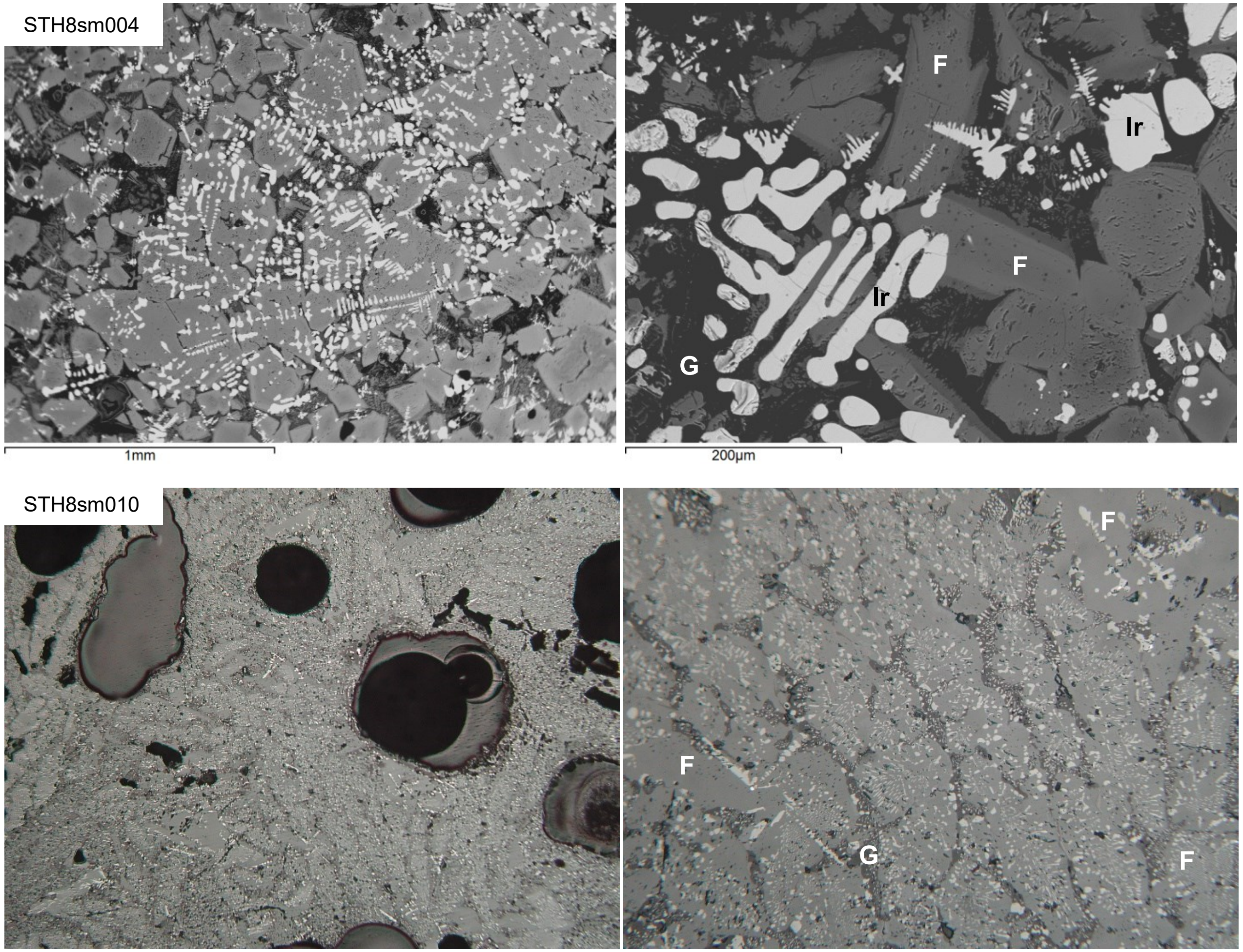


Figure 8.79 Microstructure of plano-convex shaped slag from STH8 T1. F-fayalite, H-hercynite, Ir-iron oxide, and G-glassy matrix.

Image width ≈ 3.5mm (left) and 0.85mm (right)

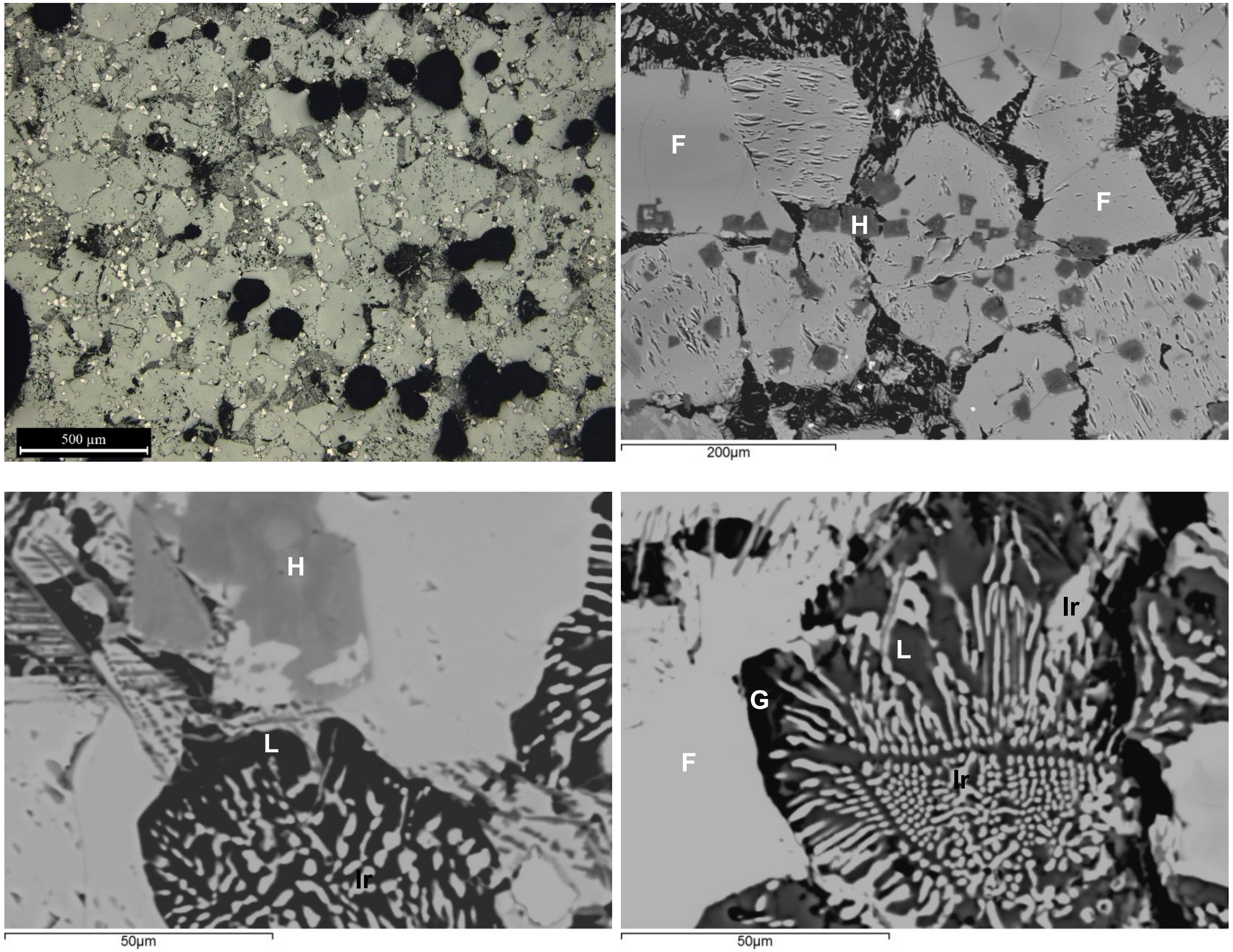


Figure 8.80 BSE images show the microstructure of STH8sm006. F-fayalite, H-hercynite, Ir-iron oxide, L-leucite, and G-glassy matrix.

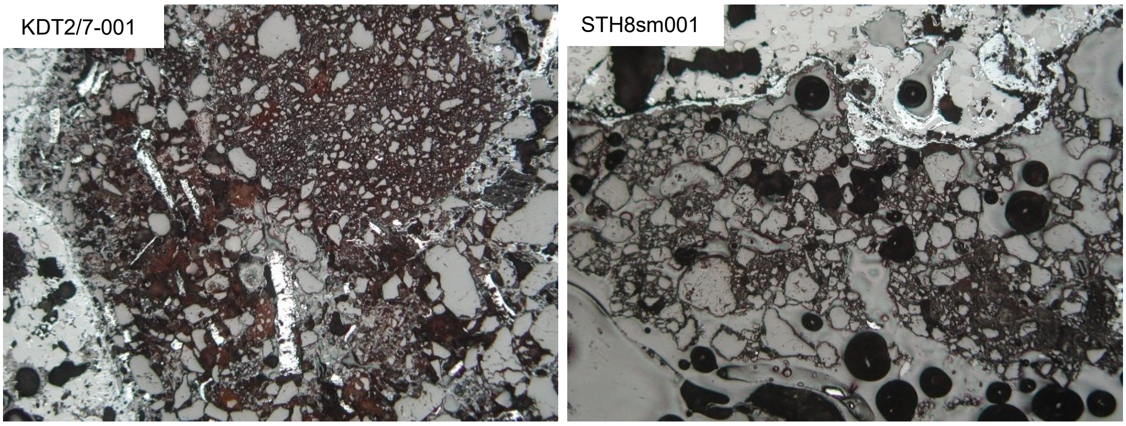


Figure 8.81 Quartz grains seen on the surface of some samples

Image width ≈ 3.5 mm.

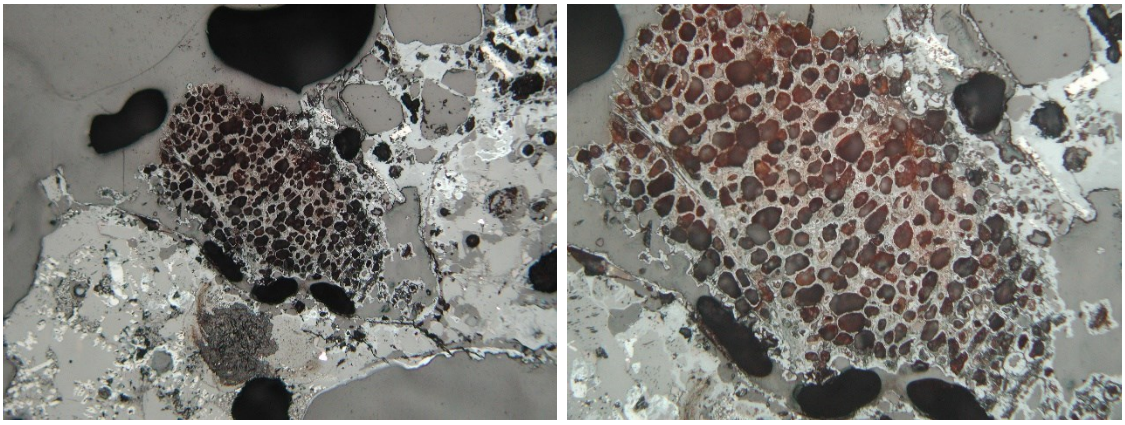


Figure 8.82 A piece of charcoal trapped in KDT2/7-001

Image width ≈ 3.5 mm (left) and 0.85mm (right).

Wüstite is a form of free iron oxide commonly found in both bloomery iron smelting and smithing slag (e.g. Bachmann 1982; Humpris 2010; Iles 2011; McDonnell 1986; Veldhuijzen 2005). It is generally formed during the reduction of iron ore: some is subsequently combined with silicon and aluminium to form fayalite and hercynite respectively, while the rest of wüstite can be reduced further into iron metal. Interestingly for Ban Kruat slag samples, wüstite can only be seen in the plano-convex slag samples. This means wüstite is newly developed during the post-smelting process, possibly in the smithing process, owing to the higher availability of iron through oxidation of the bloom.

Another interesting feature is leucite, which is a potassium-aluminium-silicate phase (Figure 8.83). Its existence seems to be suggestive of slag being formed in the environment rich in potassium, aluminium, and silicon. While aluminium and iron were already available from smelting slag, potassium could have been contributed from charcoal ashes were dissolved into the slag. In the smithing process (primary or secondary), slag is produced by the fusion of smelting slag that is expelled out of the iron, hearth lining, and fuel ashes that are typically abundant in the smithing hearth. Since slag generally rests long enough in a charcoal-rich environment, it has more time to absorb potash, which is one of the oxides abundantly present in charcoal. This fuel ash related oxide is then combined with available silica and alumina to form the leucite phase. Other indicator of this slag being formed in a charcoal-rich environment may be the phases rich in CaO (20-22 wt%) interspersed in between glassy matrix which is also rich in K_2O (10-12 wt%), CaO (4-6 wt%), and P_2O_5 (4-6 wt%) and on the edge of fayalite (Figure 8.83).

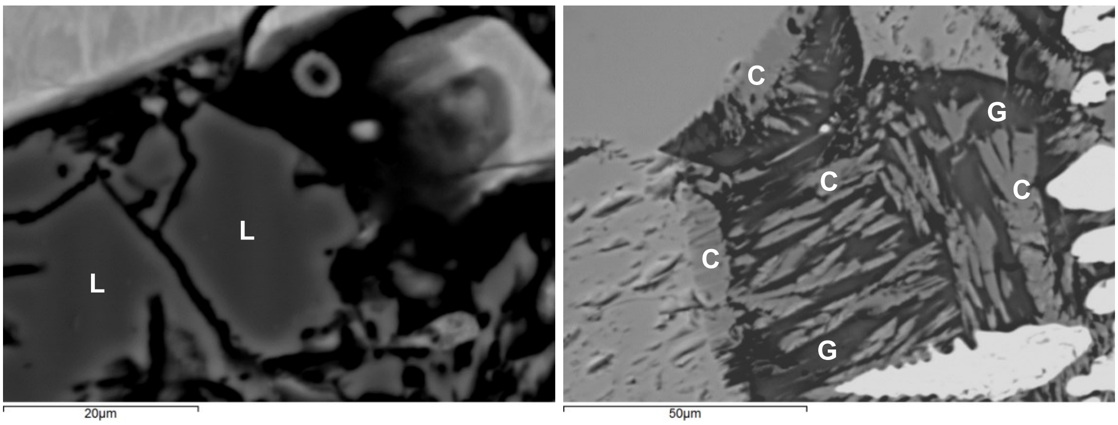


Figure 8.83 Leucite phase (L) (left) and calcium-rich phases (C) superimposing glassy matrix (G) in the plano-convex shaped slag samples.

All in all, the hammerscale flakes in these samples are the strongest line of evidence supporting the identification of these samples as smithing slag (Figure 8.84). This residue consists of iron oxide scales that break off from the surface of metallic iron by hammering in the hot state or thermal shock (McDonnell 1986, 1991; Starley 1995). It has to be reminded, however, that there no hammerscales or other comparable residues were recovered during the excavations at the locations associated with this type of slag, regardless of the use of magnet in searching.

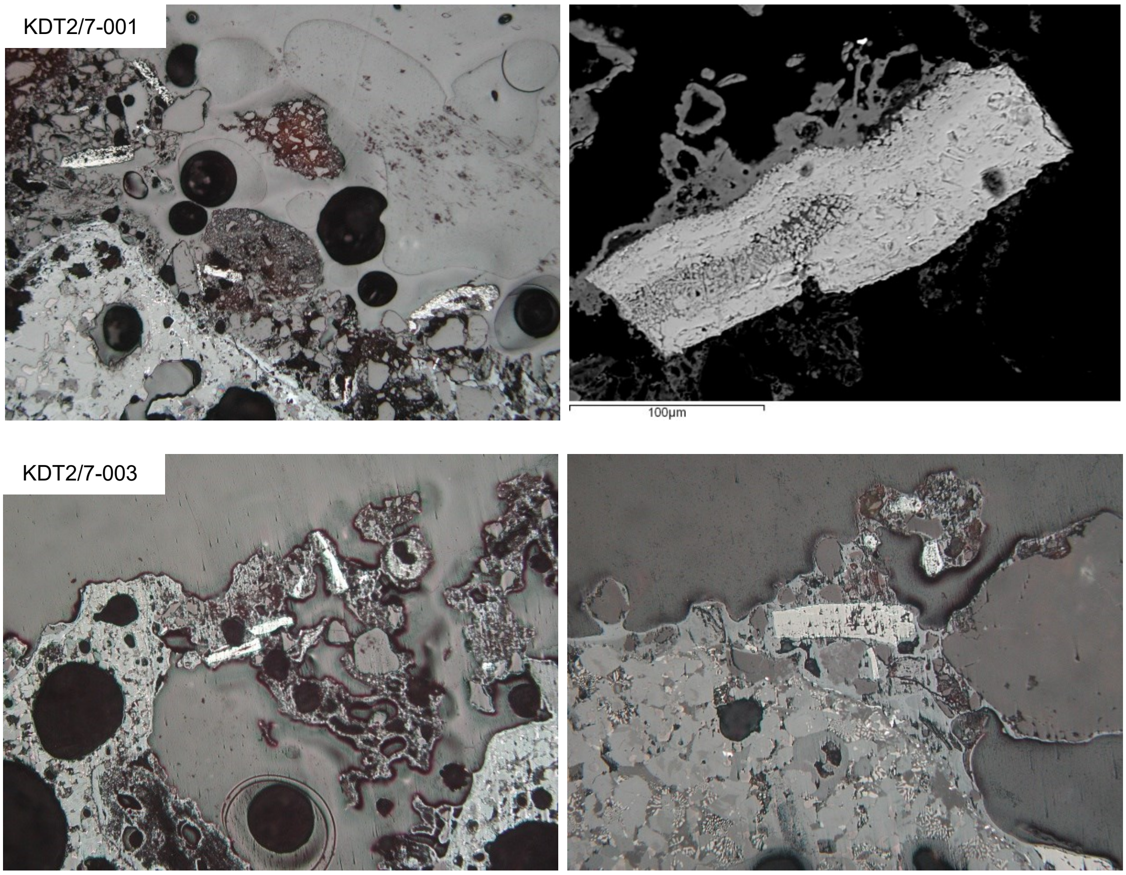


Figure 8.84 Micrographs and BSE image show hammerscale fragments (long rectangular shape) trapped in slag

(Image width is approximately 3.5 mm)

Bulk chemical analysis was also employed to better understand the chemistry of these samples (Table 8.14 and 8.15). Similarly to smelting slag, SiO_2, Al_2O_3, and FeO remain the principal components in these slag, while P_2O_5, K_2O, CaO and MnO and TiO_2 are also present in minor concentrations. Noticeably, however, the relative proportions among these oxides differ significantly from the smelting slag group (Figure 8.85). Compared to smelting slag, FeO in most samples increases to 66 wt% (vs 40-47 wt% in smelting slag), whereas Al_2O_3 and SiO_2 are significantly lower: less than 10 and 30 wt% respectively (vs 14-16 wt% and 33-37 wt% in smelting slag). TiO_2, V_2O_5, Cr_2O_3, and MnO, which are associated with ores, are other compounds noticeably lower than the smelting slag. This is consistent with the idea that iron formed from the oxidation of metallic iron, rather than from the smelting slag. Conversely, K_2O and P_2O_5 are higher. CaO seemingly remains at comparable levels.

This chemical characteristic is consistent with the structural features noted above. High levels of FeO are reflected in abundant wüstite, while hercynite crystals become less common because of the lower Al_2O_3. High proportions of oxides associated with charcoal (e.g. K_2O, P_2O_5, and CaO) well conform to the formation of phases like leucite, the calcium-rich phase described above, and a calcium, potassium, and phosphorous rich glassy matrix.

	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO
KDT2/7-001	5.60	23.42	1.55	1.17	1.33	0.39	0.06	0.04	0.25	66.10
KDT2/7-002	5.30	27.62	0.92	0.75	0.97	0.31	0.07	0.03	0.15	63.78
KDT2/7-003	7.01	25.26	2.94	1.51	1.99	0.69	0.08	0.06	0.31	60.01
KDT2/7-004	16.04	36.06	0.25	0.38	1.59	1.34	0.26	0.17	0.52	43.12
KDT2/7-005	3.18	29.80	1.42	1.57	2.13	0.20	0.03	0.02	0.28	61.24
KDT2/7-006	5.90	19.41	2.26	0.90	1.13	0.45	0.07	0.05	0.41	69.30
Mean	5.40	25.10	1.82	1.18	1.51	0.41	0.06	0.04	0.28	64.08
SD	1.4	4.0	0.8	0.4	0.5	0.2	0.0	0.0	0.1	3.7
CV	26	16	43	31	35	46	33	36	34	6
STH8sm001	7.64	25.33	0.53	1.26	2.29	0.19	0.12	0.05	0.26	62.20
STH8sm002	9.59	72.53	0.38	0.40	0.33	0.48	0.07	0.05	0.06	15.97
STH8sm003	4.43	21.95	0.35	0.67	0.50	0.12	0.05	0.03	0.07	71.76
STH8sm004	1.56	25.36	1.30	0.97	3.55	0.08	0.01	0.01	0.09	66.99
STH8sm005	9.70	36.17	0.39	2.80	2.69	0.25	0.09	0.04	0.17	47.54
STH8sm006	7.14	25.47	2.30	0.85	2.00	0.88	0.08	0.06	0.64	60.41
STH8sm007	14.73	36.02	0.18	0.42	0.80	0.48	0.22	0.07	0.06	46.93
STH8sm008	6.60	25.37	0.49	0.77	1.50	0.18	0.08	0.03	0.27	64.56
STH8sm009	5.22	25.97	1.02	0.70	1.23	0.36	0.05	0.05	0.07	65.26
STH8sm010	8.60	29.50	0.42	1.33	1.62	0.24	0.12	0.04	0.51	57.33
STH8sm011	5.28	29.83	0.85	1.41	1.14	0.26	0.05	0.03	0.15	60.91
STH8sm012	1.44	28.17	0.58	0.42	0.53	0.05	0.01	0.01	0.03	68.69
Mean	5.32	26.33	0.87	0.93	1.59	0.26	0.06	0.03	0.23	64.23
SD	2.5	2.5	0.6	0.3	0.9	0.3	0.0	0.0	0.2	4.5
CV	47	9	71	36	59	96	61	52	92	7

Table 8.14 WD-XRF chemical data of selected oxides for convex shape slag samples, normalised to 100%. The samples with grey alphabets are probably not smithing slag, but smelting slag due to the differences in chemical signature, thus not included in the calculations of Mean, SD and CV. STH8sm002 is of interest for its high level of SiO_2 which may be interpreted as cinder (a silica-rich intermediate production between hearth lining and smithing slag (McDonnell 1991, 23)), but more information is required to verify this speculation.

	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3
KDT2/7-001	46	36	97	69	171	542	23	56	82
KDT2/7-002	5	17	74	58	206	357	114	161	82
KDT2/7-003	68	76	109	103	229	462	72	204	30
KDT2/7-004	72	75	41	118	775	972	0	582	67
KDT2/7-005	57	5	213	128	131	668	64	84	2
KDT2/7-006	69	27	68	68	149	735	100	102	52
Mean	49	32	112	85	177	553	75	121	50
SD	26.3	27.1	58.8	29.2	40.5	152.5	35.5	59.8	34.5
CV	53	84	52	34	23	28	48	49	69
STH8sm001	51	26	109	107	255	407	45	420	27
STH8sm002	40	60	44	25	565	759	21	63	bdl
STH8sm003	157	67	108	12	114	304	14	bdl	bdl
STH8sm004	68	1	78	177	50	460	34	bdl	bdl
STH8sm005	43	16	303	130	362	629	bdl	100	bdl
STH8sm006	bdl	4	74	110	320	1015	78	71	26
STH8sm007	88	73	34	37	513	147	39	33	10
STH8sm008	59	16	84	87	236	637	32	266	25
STH8sm009	26	bdl	68	50	221	310	14	bdl	bdl
STH8sm010	89	66	151	105	393	1254	70	942	25
STH8sm011	55	8	113	48	173	370	28	14	bdl
STH8sm012	195	bdl	41	18	119	53	111	95	49
Average	83	21	92	79	209	534	47	206	28
SD	55.7	27.2	32.0	52.4	107.8	378.1	32.6	310.1	7.9
CV	67	128	35	66	52	71	69	151	28

Table 8.15 WD-XRF chemical data of selected oxides for convex shape slag samples, normalised to 100% (continued)

The chemical characterisation of these samples thus reinforce the macroscopic difference between these and the smelting slag. The difference becomes clearer when plotting both slag groups in the same FeO-Al_2O_3-SiO_2 ternary diagram (Figure 8.86). All convex shaped slag samples fall into the fayalite region, separate from the smelting slag, suggesting the operation was conducted within the range of temperatures used in smelting process or relatively lower but with different proportions of the main oxides. Convex shaped slag samples are always consistent with fayalite region due to high quantities of iron, whereas smelting slag samples consistently fall into hercynite region due to their aluminium-rich nature.

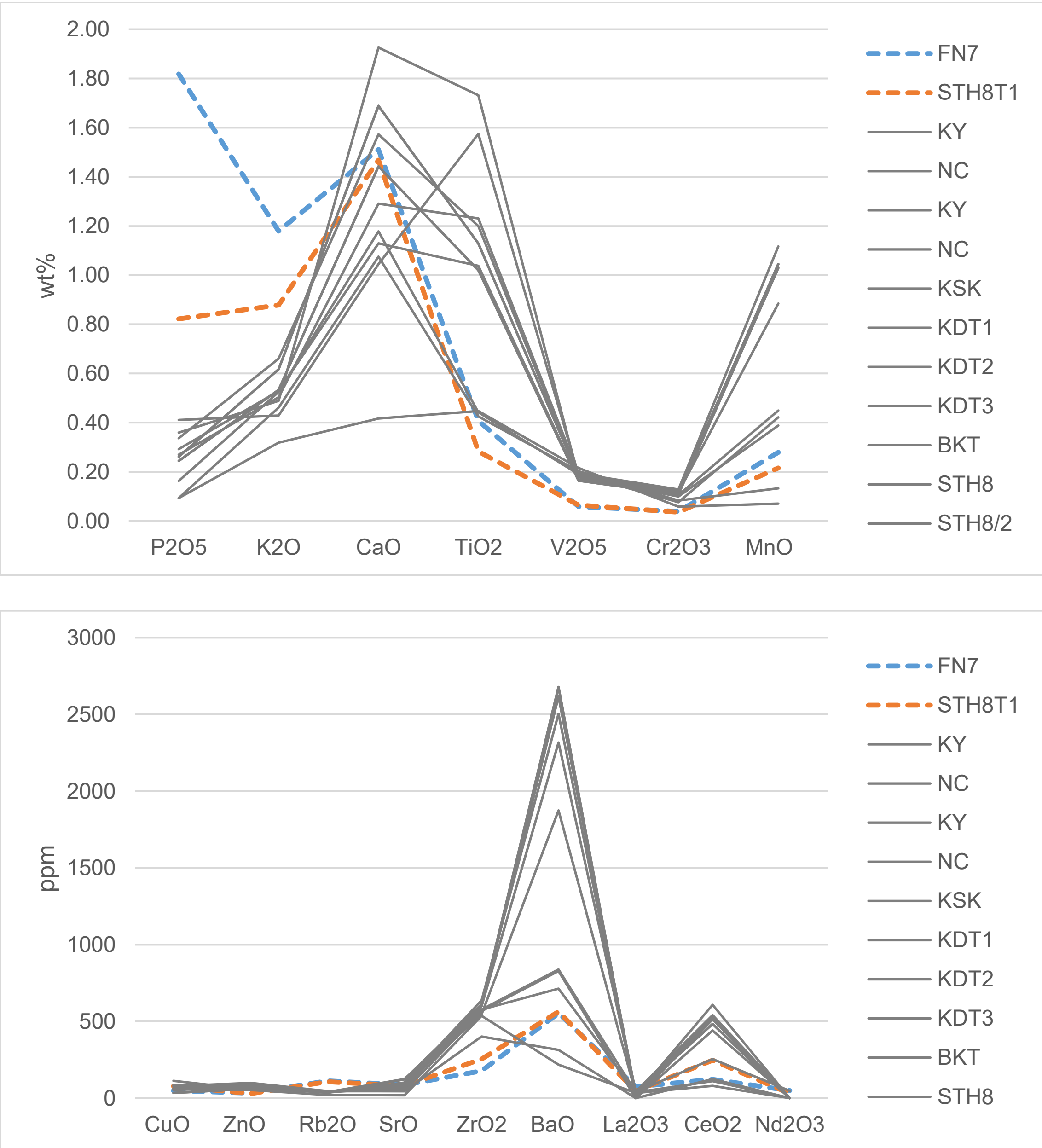


Figure 8.85 Line plot shows a cross-comparison of oxide values between the smithing (dashed lines) and smelting (solid grey lines) slag samples, calculated from average bulk chemical data of each group.

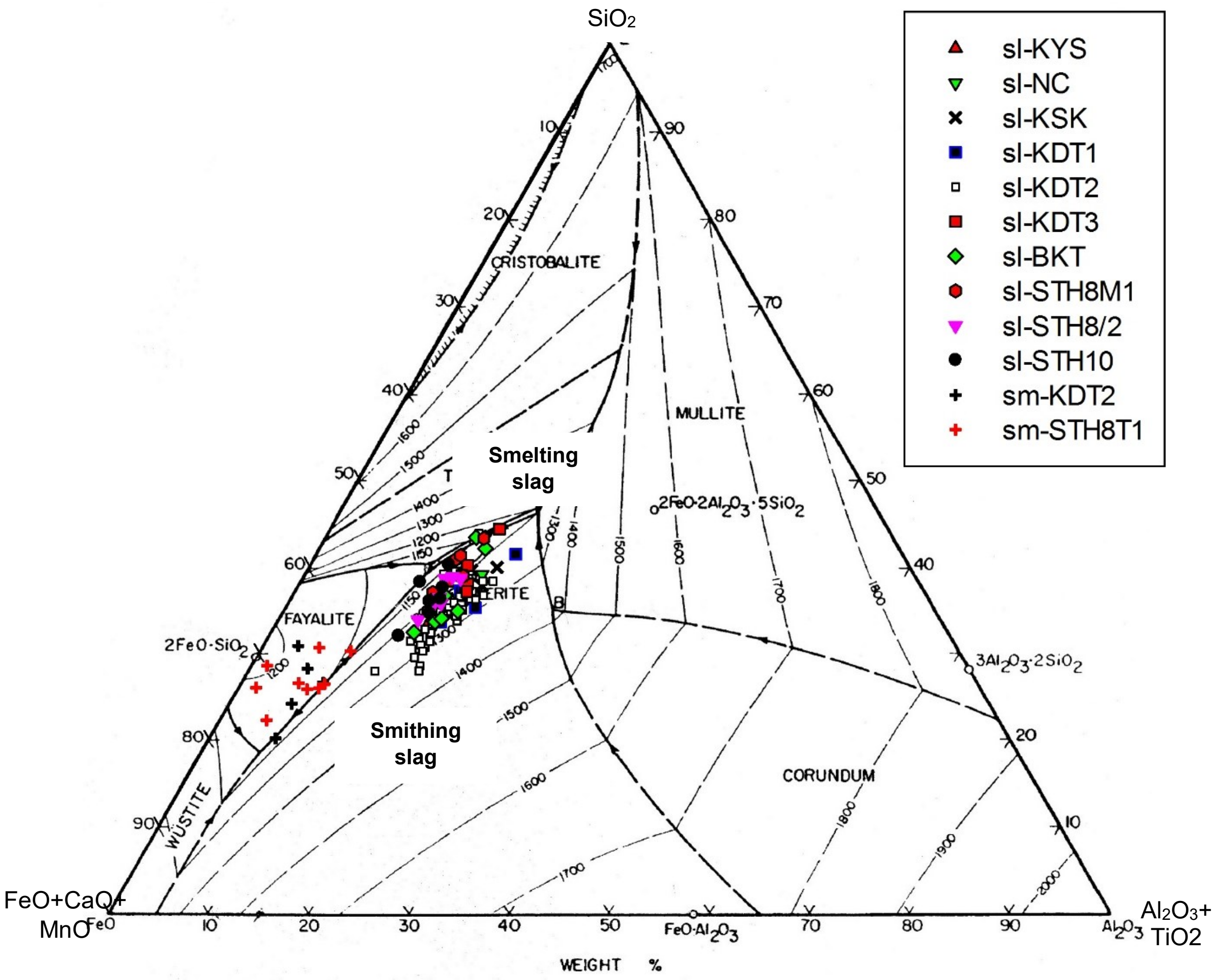


Figure 8.86 A ternary diagram of the FeO(+CaO+MnO)-SiO_2-Al_2O_3(+TiO_2) system shows two discernible slag groups: amorphous slag/slag blocks and plano-convex shaped slag

8.3.3.2.1 Discussion and summary

This group of slag is different from any other slag material recorded and, as discussed earlier and in Chapter 7, it constitutes a minority of the assemblage. This slag group, consisting of dense slag with convex bottoms, was found in the specific contexts. At KDT2, only small quantities of this slag were found, though still in the area with smelting activity; while at STH8, the slag was found outside the smelting context as a thick layer surrounding a feature that may have been a hearth for smithing (see section 7.2.7.1). The appearance of this slag is arguably characteristic of smithing activity (McDonnell 1991; Serneels and Perret 2003; Veldhuijzen 2005, 185-187) and obviously different from smelting slag.

Their unique characteristics are reinforced by the microstructural examination and microanalysis. Chemical compositional characteristic of this slag, reflected in the microstructures, distinguishes this from smelting slag. High levels of iron and charcoal-related compounds (e.g. P_2O_5, CaO, and K_2O) and low levels of smelting-related elements (e.g. TiO_2, MnO, and Al_2O_3) detected demonstrate that this slag was associated with smithing in a charcoal-rich and oxidised environment. In this sense, it is important to emphasise that the predominant form of free iron oxide as wüstite is not an indication of reducing atmospheres (from higher oxides in the ore) but rather, most likely, the result of oxidation of metallic iron being heated for smithing. The microanalysis also identified the remains of hammerscales embedded in the slag, further corroborating this interpretation.

These findings thus strongly suggests that this slag originated from the smithing process, and that post-smelting stages were carried out at least at some of the ironworking workshops.

The data generated also allow to model the formation of smithing slag in this context. Their shapes, as mentioned previously, indicate that they were formed at the bottom of the hearth with a convex profile through an agglomeration of the materials (e.g. oxidised iron, slag expelled out of the bloom, hearth lining, charcoal ashes and possible sand flux) from various smithing episodes. Chemically, the slag can carry some elements from the smelting slag, as some of this slag is expelled out of the metallic iron during the process; however, other components other than ores and smelting fluxes become more influential in the slag, with hearth lining, charcoal ashes and oxidised iron principally contributing elements, especially iron, phosphorous, calcium, and potassium. The last three elements were arguably from iron or charcoal ashes (McDonnell 1991; Serneels and Perret 2003). Due to this process, some oxides are emphasised or increased, while others decrease, compared to the smelting slag. This pattern is seen in these samples. Influenced by the surplus iron and potassium, the resulting microstructure is different, with the presence of wüstite and leucite. It is not clear if sand was added as a flux to promote the formation of slag in order to clean the surface of the metal worked (McDonnell 1991, 25). The microstructure appears to be relatively free of quartz dominated regions. Moreover, quartz particles were seen in the core region of a few slag samples, while others tend to have the particles adhered on the edge, possibly from contacting the wall of the hearth. On this basis, it seems acceptable to state that, if a sand flux was used at all, the addition of sand was not in a large quantity (Serneels and Perret 2003).

8.4 Technological interpretations of analytical results

As the analytical data for all smelting components, except fuel ash, were presented with some interesting features highlighted, this section will present a more detailed analysis and interpretation of the technical parameters of the smelting remains in order to shed new light upon how iron smelting was conducted. Questions highlighted in previous sections will be addressed. Further discussion about iron smithing slag is also presented here.

This technological interpretation (e.g. smelting condition, mechanism, and possible final product) will be evaluated together with associated social contexts (see Chapters 3, 4, and 6) in order to present a reconstructed *chaîne opératoire* of Ban Kruat iron production and understand the place of this production in the social development of Ban Kruat and lower Northeast Thailand.

8.4.1 Formation of smelting slag and its implications for smelting conditions and mechanisms

As discussed in section 4.2, slag is considered the most valuable source of process information for iron production. Understanding the formation of slag can reveal the furnace conditions and reduction mechanisms. To elucidate these aspects, the physical and chemical properties of the slag and related smelting components, presented previously in section 8.3.3.1, are explored again and evaluated here. Some issues also need to be addressed and clarified first, including slag liquidus temperatures, slag viscosity, the contribution of different components to slag formation, and reduction efficiency.

8.4.1.1 Slag liquidus temperatures and viscosity of smelting slag

Chemical data can be used to estimate the melting ranges and viscosity of slag by plotting them onto corresponding diagrams (Bachmann 1982, 13; Freestone 1988). When microscopic analyses confirm that the slags were fully molten (as is the case for most samples here), phase diagrams can help estimate the minimum temperatures the furnace achieved during the operation; although, the actual temperatures can be higher by several hundred degrees (Freestone 1988, 49).

When plotted on the FeO-SiO_2-Al_2O_3 diagram (Figure 8.65-8.68), the slag concentrates in the hercynite region, which concurs well with abundant hercynite crystals and absence of wüstite crystals seen in the micrographs presented above. Most Ban Kruat smelting slag samples plot in the region with melting temperatures around 1,200°C and 1,300°C, with some extremes on the 1,150°C and beyond the 1,300°C isotherms. Those falling above the 1,300°C lines are likely to be influenced by lower iron oxide and higher alumina contents (Figure 8.65-8.68). No correlation is found between the structural subgroups and the melting temperatures. According to the diagram, slag liquidus temperatures are estimated to be around 1,200-1,300°C.

This range of estimated melting temperatures is considered higher than typical bloomery slag whose melting range is generally around 1,150-1,200°C (Morton and Wingrove 1969, 1564; Rostoker and Bronson 1990, 91). One of the factors raising the melting point is the high alumina levels (14-16 wt%) in the slag.

It is also possible to discuss the viscosity of this slag; although, an experimental approach is needed to obtain an accurate determination (Freestone 1988; Kresten 1986). As discussed in sections 4.2 and 8.3.1.2, alumina and silica, in conjunction with iron oxides play a major role in determining the viscosity of slag at a given temperature. In the Ban Kruat case, analyses indicate that high alumina is likely a major influence in the material properties and behaviour of the slag; however, the effect of this oxide on slag viscosity cannot be accurately determined without systematic measurements (Chen *et al.* 2013, 820). In this study, a rough estimation of Ban Kruat slag viscosity was drawn from the laboratory measurements of FeO-SiO_2-Al_2O_3 slag system reported by Chen *et al*. (2013).

According to the paper, the viscosity of slag with the composition of 40.0 wt% SiO_2, 40.2 wt% FeO, and 19.8 wt% Al_2O_3 at the temperature of 1,405°C was 0.614 Pa·s (6.14 poise), while slag with the composition of 40.3 wt% SiO_2, 48.4 wt% FeO, and 11.3 wt% Al_2O_3 at 1,300°C had the viscosity of 0.533 Pa·s (5.33 poise). The viscosity of fayalitic slag (31.2-35.6 wt% SiO_2, 60.0-65.8 wt% FeO, and 3.0-4.4 wt% Al_2O_3) was determined to be less than 0.17 Pa·s (1.7 poise) at 1200°C (Chen *et al.* 2013, 822; see also Paynter 2007, 207). Ban Kruat smelting slag are around 33-38 wt% SiO_2, 40-48 wt% FeO, and 13-16 wt% Al_2O_3. Based on Chen's determinations, the viscosity of Ban Kruat slag may be safely estimated to be around 0.5-0.6 Pa·s (5-6 poise) at 1,300°C. The viscosity increases as the temperature decreases, and vice versa. Thus, the estimated viscosity of Ban Kruat slag is possibly 2-3 times higher than typical bloomery smelting slag.

These data suggest the operating temperature of the Ban Kruat furnaces was possibly around 1,200-1,300°C with a possibility of higher temperatures around 1,400°C reached. Even at this temperature range, the slag is more viscous than typical bloomery slag forming at lower temperatures. This information will be revisited in the following sections.

8.4.1.2 Determination of the contribution of various materials to the formation of the slag

Slag formation is dictated mainly by three components involved in smelting (i.e. ore, technical ceramic, and fuel), in addition to the redox and temperature. Furthermore, ore is known to contribute most to the slag chemistry followed by clay and ash (Crew 2000, 2013; Serneels and Crew 1997; Thomas and Young 1999). Their relative contributions define the slag chemistry and, to some extent, their physical properties (e.g. fluid or viscous). Smelting conditions are also responsible for the latter properties of the slag. Thus, in order to better understand the formation of Ban Kruat smelting slag, it is essential to determine how various components contributed to slag formation. The issue of laterite smelting and quality of laterite in this smelting system will also be evaluated in this section.

This exercise employed materials balance calculations to evaluate the feasibility of this smelting system (i.e. a system utilising this ore and technical ceramics associated) and the possible yield obtained. As laterite is proposed to be the ore smelted, it was necessary to verify first to what extent the archaeological laterite (possible ore specimens) had a relationship with the smelting slag. The evaluation of ore-slag relationship would be performed through an examination of relevant oxides such SiO_2, Al_2O_3, TiO_2, and MnO, and their ratios.

8.4.1.2.1 Ore-slag relationship: evaluating the hypothesis of laterite as an ore

As presented previously, the hypothesis of the laterite smelting seems to be supported by both archaeology and analytical results. These include an association of laterite with smelting context (see section 7.3.2.3), the unreacted laterite fragments in some slag, and the high alumina nature of both slag and laterite (see section 8.3.1 and 8.3.3.1). Nonetheless, these are still debatable. The laterite fragments could have come from local clay in which laterite is also present, and the alumina can also be derived from alumina-rich clay utilised for the production of technical ceramics.

An exploration of relevant oxide ratios, particularly SiO_2:Al_2O_3, (or *F*-value (Buchwald 2005; Charlton 2007, 157; Charlton *et al*. 2010)) may help clarify this issue. This SiO_2:Al_2O_3 ratio is argued to preserve a constant ratio between ore smelted and slag produced and can also be used to identify any changes in the ore smelted (Charlton *et al*. 2010, 356; Thomas and Young 1999, 223). Comparing the SiO_2:Al_2O_3 ratio among the materials, there is a noticeable difference between the ore (1:1.6-5.7) and technical ceramic SiO_2:Al_2O_3 ratio (1:4.3-13.5), while the slag SiO_2:Al_2O_3 ratio is more consistent (1:1.7-2.3). The ore SiO_2:Al_2O_3 ratio appears to better match the slag than technical ceramics, indicating that the ore would be the dominant contributor of these oxides to the slag. This seems to be supported by the characterisation of technical ceramics that showed this material being fairly refractory (see section 7.3.2.2 and 8.3.2), thus likely contributing relatively little to slag chemistry through melting. Although this SiO_2:Al_2O_3 ratio tends to be consistent with the hypothesis, we still need to explain the slight difference in the SiO_2:Al_2O_3 ratio between the laterite and slag. The slag generally contains comparable levels of alumina to those in the laterite analysed, but less silica. A plot of the ore SiO_2:Al_2O_3 ratio against FeO shows that there is a broad correlation between these two values (i.e. the higher the FeO, the lower the SiO_2:Al_2O_3 ratio) (Figure 8.87). More importantly, it shows that laterite with FeO higher than 55 wt% have a SiO_2:Al_2O_3 ratio of 1.5-2.5, very close to the slag SiO_2:Al_2O_3 ratio, raising the possibility that iron-rich laterite was preferentially selected. Although silica is lower in the ore than in slag (20-30 vs 38-40 wt%), the depletion of FeO from the system would lead to a SiO_2 enrichment in slag (Severin *et al*. 2011, 989). The materials balance calculation below may help clarify this issue. If this is found to be a plausible scenario, the implication would be that local smelters specifically went for FeO-rich laterite nodules (at least more than 55 wt% FeO) which would ensure successful smelt, as discussed. However, it is not clear how different qualities of laterite nodules could be recognised in the past. One possibility was to sort them by density as FeO-rich nodules may have been denser, thus heavier than FeO-poor ones. The pieces with visible large quartz (higher SiO_2:Al_2O_3 ratio) may have helped local smelters to sort them out.

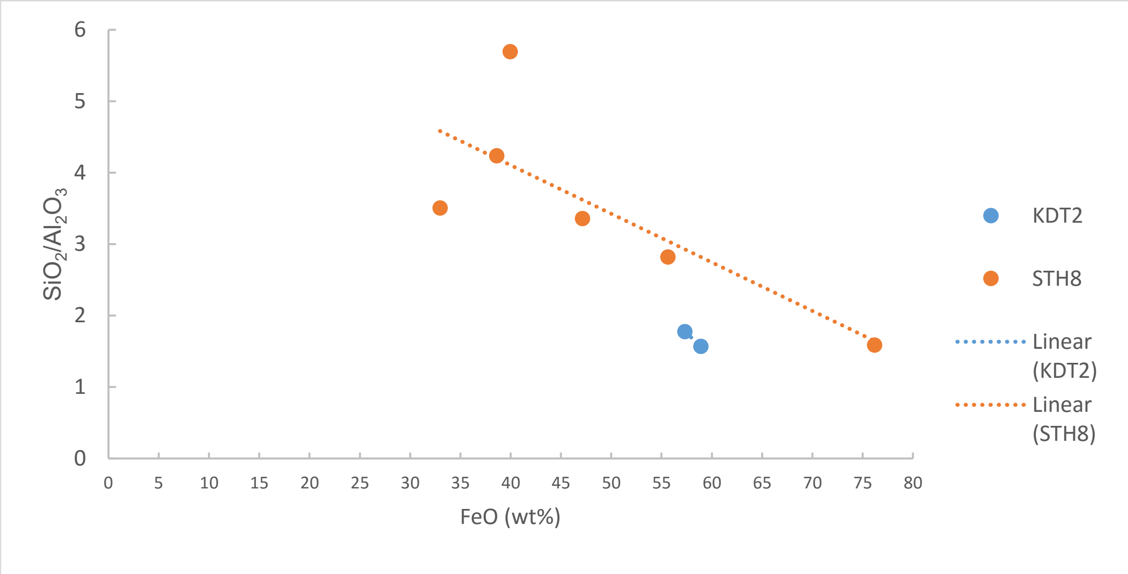


Figure 8.87 Scatter plot shows SiO_2 and Al_2O_3 ratio and FeO values of laterite ore samples. Calculated from WD-XRF data normalised to 100% (Table 8.3).

Another approach to assess to what extent technical ceramics contribute alumina to the slag is to examine the Al_2O_3:TiO_2 ratio. These oxides are also present in both clay and ore (Ige and Rehren 2003; Senn *et al*. 2009, 138). The chemical analysis of slag samples showed that they can be divided into titania-rich and titania-poor groups (see section 8.3.3.1.1.2). Therefore, a comparison of Al_2O_3:TiO_2 ratio was performed separately for each group using corresponding laterite samples (i.e. the KDT2 laterite samples for the western group and the STH8 samples for the eastern group). The result shows a fair agreement in each comparison of Al_2O_3:TiO_2 ratio: the western group – slag 1:9-13 and laterite 1:3-10 and the eastern group – slag 1:29-33 and laterite 1:28-35. Though one may argue that the clay might contribute this oxide to the slag, this does not seem to be the case to any significant extent as the Al_2O_3:TiO_2 ratio of the technical ceramics in Ban Kruat is consistent around 1:20-27. Thus it can be stated that the bulk of the TiO_2 in the slag was also contributed by the ore.

MnO is another oxide that can directly confirm the relationship between ore and slag as it is entirely derived from the ore and will largely concentrate in the slag when smelted (Iles 2011, 2014). In this case, however, the assessment was made impossible because of the high MnO variation in the ore and slag, as demonstrated by the CV values (190 for laterite and 23-98 for slag).

All in all, and with the caveats noted, the analysis of the chemical data substantiates the use of laterite in iron smelting in this area. The evaluation of the oxides above also suggests that SiO_2, Al_2O_3, and TiO_2 were likely contributed mainly by the ore rather than the clay, i.e. molten technical ceramics only contributed a small quantity of these oxides to the slag. The consistency of the slag SiO_2:Al_2O_3 ratio further indicates that there was a consistent set of practices in terms of furnace charge and operating parameters, possibly with preferential selection of Fe-rich laterite. This latter point will be elaborated on (see section 8.4.2).

8.4.1.2.2 Materials balance calculations and yield estimation

The method to evaluate the relationship between different components and slag is to estimate the materials balance for each component and possible yield obtained from such a system. Several models have been proposed for this evaluation (see Charlton 2007, 149-154 for a review of existing models). Of these, this study employed the model proposed by Crew (2000) for this task. Unlike the models by Serneels (1993 in Charlton 2007), Joosten (2004), and Joosten and Kars (1999), which focus mainly on the influence of ore and clay (SiO_2 and Al_2O_3), the Crew model considers the relative contribution of all relevant components (ore, clay, and ash) to slag chemistry, thus providing a better estimation of materials balance. The model also allows a wider range of oxides to be observed (Charlton 2007; Crew 2000, 2013; Dungworth 2009, 17). To explain the materials balance, the model uses an informatively graphical representation to find the best fit between different compounds and slag. The calculation involves the use of an enrichment factor (EF) that estimates the enrichment of ore oxides in the slag as iron is removed from the system as metal product. This is done following the equation:

$$\mathrm{EF} = \frac{(\mathrm{SiO2+Al2O3})\mathrm{slag}}{(\mathrm{M}\times(\mathrm{SiO2+Al2O3})\mathrm{ore})+(\mathrm{P}\times(\mathrm{SiO2+Al2O3})\mathrm{clay})+(\mathrm{C}\times(\mathrm{SiO2+Al2O3})\mathrm{ash})}$$

M, P, and C stand for the proportion of ore, clay, and ash respectively. With these factors calculated, the materials balance can be done through this calculation for each compounds:

$$((M_{ore} \times C_{ore}) + (P_{clay} \times C_{clay}) + (C_{ash} \times C_{ash})) \times \mathrm{EF} = \text{Mass Balance}$$

These values can be compared with the chosen slag chemistry on a line graph (Charlton 2007, 152-153; Crew 2000). A fit between the components and the slag may be considered “good” if the differences between oxides are within 10% relative of the measured concentrations, particularly SiO_2, Al_2O_3, TiO_2, CaO, and MnO (Charlton 2007, 199, 253). The yield of the production is estimated by production / Fe in ore (Crew 2000, 41).

In order to reach an acceptable result, the calculation requires a set of good representative chemical data for all materials. This already raises concerns for the calculations for Ban Kruat smelting system. Firstly, no chemical data for charcoal used is available for this study. The contribution of ash to slag chemistry is known to vary according to type of fuels, species, geology, and part of the tree used, in addition to the charcoal to ore ratios (Charlton 2007, 198; Crew 2000). The main fuel ash compounds are Na_2O, MgO, K_2O, CaO, Rb_2O, SrO, BaO, and probably P_2O_5 (Crew 2000, 39; Desaulty *et al*. 2009, 2449); therefore, one may assume the origin of these oxides to be primarily from the fuel used. However, some of these oxides can also be contributed by clay (e.g. Cao and BaO (Desaulty *et al*. 2009, 2449)) and ore (P_2O_5) (Salter and Crew 1997; Buchwald 2005) as well.

In the Thai context, a hard and dense type of wood is likely to have been used as the source of charcoal for ancient iron smelting, but the species and its chemistry, has yet to be identified (Suchitta 1983, 187-188). The SEM-EDS analysis of the charcoal fragment in one of the Ban Kruat slag samples identified only CaO as a main constituent, as it could not detect the carbon content (see section 8.3.3.1.1.1), but these data cannot be taken at face value.

Secondly, the chemical heterogeneity of laterite ores can cause a problem in balancing the oxides between the ore and slag. While all the ores share a relatively high alumina content, other oxides vary from sample to sample, especially MnO. Moreover, there is also a possibility that different grades of ore were blended and smelted, and that ore samples collected may be discarded ore pieces. This means that the ore analysed may not represent the actual ore smelted, thus becoming impossible to obtain a “good” result. Owing to these constraints, the following calculations only provide a crude estimate of the smelting system based on available finds but are hoped to be informative enough to suggest how each component contributed to the slag chemistry.

In order to use samples from consistent contexts, only KDT2 and STH8 were considered. This was justified by the fact that archaeological laterite samples were only found at these sites. For KDT2, the laterite samples were found in association with the furnace 1 and 2 (KDT2e001 and 002); therefore, the slag samples from the same context (KDT2-007-021) were included for this evaluation. No technical ceramic samples from the same context were available for the analyses, so samples from a nearby furnace (#5) were used (KDT2FF001 and 002). For STH8, the laterite samples (STH8e001-006) were found in a context unrelated to the smelting activity. To permit the calculation, the slag (STH8-001-007) and technical ceramics (STH8M1CP and STH8M1FF) from Mound 1 were included. The results below only show resultant graphs, while the relevant chemical data for all materials are provided in Appendix K.

The order in which the oxides are represented follows the convention by Crew (2000, 39) to show the influence of the clay (SiO_2 to ZrO_2) and ash (K_2O to BaO) as well as those oxides depleting in slag and partitioning to the metal (as an element) (V_2O_5 to P_2O_5). The yield estimated from each calculation is given, but the implications of these latter figures will be discussed the next section concerning reduction efficiency.

KDT2

The first model to be discussed is the materials balance of the KDT2 samples from furnaces 1 and 2 (Figure 8.88). While fits for SiO_2, Al_2O_3, V_2O_5, and Cr_2O_3 are below 10% and ZrO_2 below 15% relative, it was impossible to bring the fit for other oxides below 10%. As discussed earlier, the extent to which the ore sample is representative can be questionable; however, the best fit marks the ore as the key influence in the slag chemistry, with a very small contribution from the clay. It is clear that the ash compositional data would make the balance fit better to the mean, especially K_2O and CaO. In this setting, the materials balance indicates a production efficiency of 7% (i.e. 7g iron per 100g slag), which is a yield of c. 13% from the iron in the ore.

A calculation was also performed on the same ore data but with the average of all KDT2 slag and technical ceramics analysed (Figure 8.89). A very similar result was reached, but, in this setting, the calculation infers that more contribution from the clay would be required to produce this modelled slag in addition to the ash for the ash oxides. Interestingly, this smelting system would be able to extract only 5% of iron from the ore and produce 2% of iron.

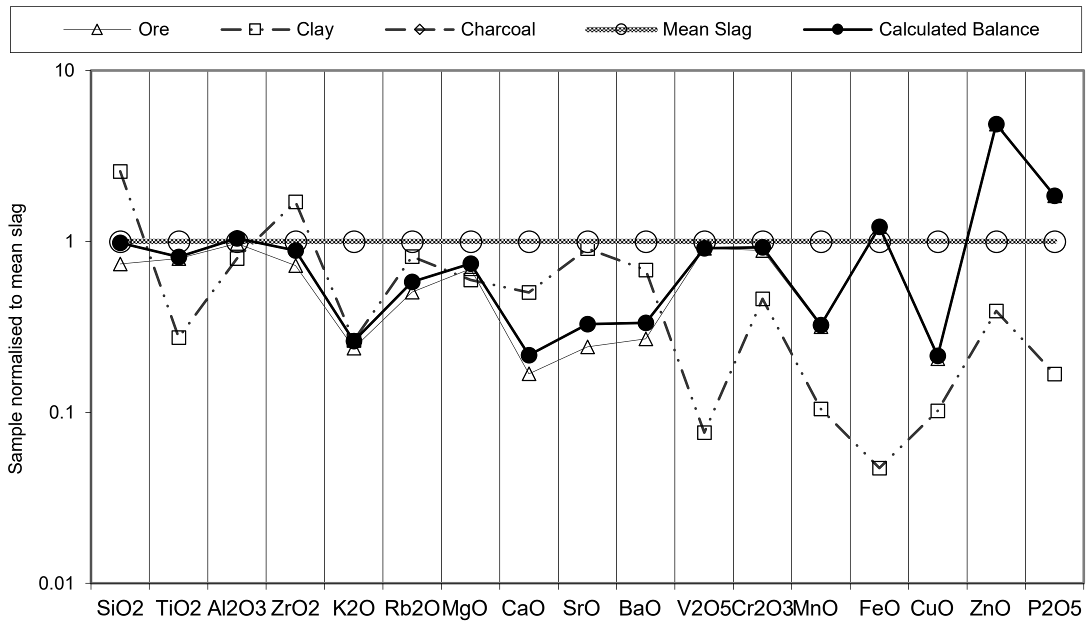


Figure 8.88 Best-fit materials balance solution for the average of each KDT2 materials from the furnace 1 and 2. EF=1.088, 91% ore + 9% clay. A production of Fe approximately 7%, Fe Yield of some 13%.

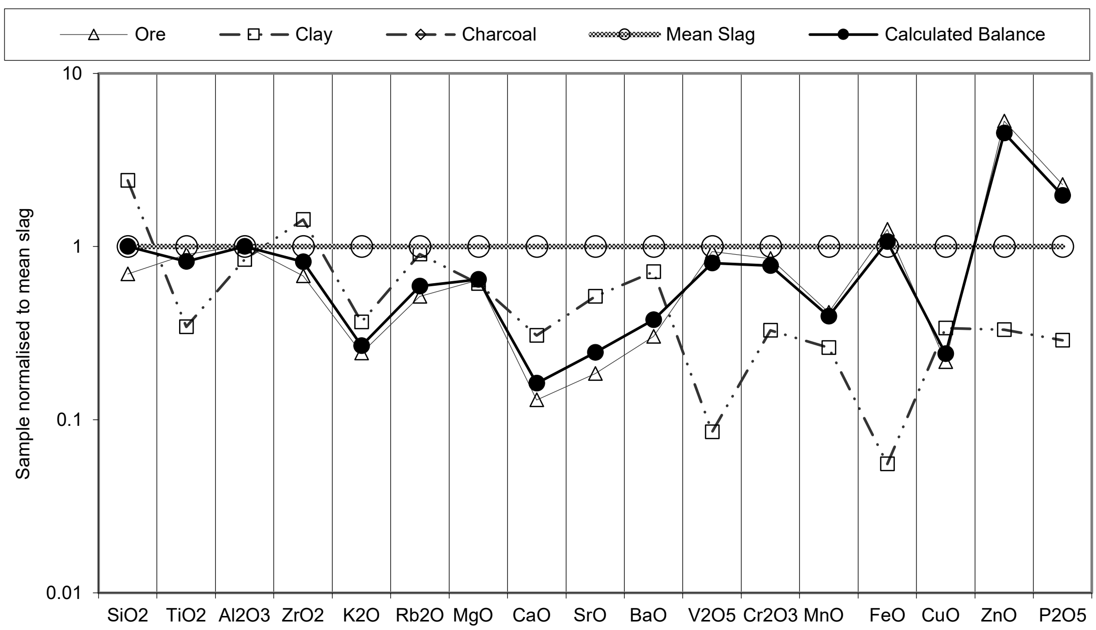


Figure 8.89 Best-fit materials balance solution for KDT2 with the average of all KDT2 slag and technical ceramics. EF=1.015, 83.1% ore + 16.9% clay. A production of Fe approximately 2%, Fe Yield of some 5%.

STH8

In order to test the hypothesis that iron-rich and silica-rich laterite could have been blended for smelting, data for all the ore samples from this context were averaged. The balancing faced more difficulties in comparison to the KDT2 case, resulting in over 10% relative differences for all oxides, except SiO_2 and ZrO_2 (Figure 8.90). The mass balance again suggests the ore as the main contributor, and the yield estimation is similar to the first KDT2 calculation with 5% iron production estimated and yield of some 9% from the ore.

A better mass-balance fit is obtained, however, when the hypothesis of a preferential selection of Fe-rich laterite is tested. The mean chemical data of two FeO-rich samples: STH8e002 and 004 (55 and 75 wt%) were used to model the slag composition from STH8 M1 (FeO around 65 wt%, Al_2O_3 10 wt%, and SiO_2 23 wt%) (Figure 8.91). The estimated iron yield was significantly increased (to 36%) with more than 30% iron being extracted from the ore. The calculation suggests that the ore contributed most oxides present in slag, including SiO_2, with very little clay contribution.

A final calculation using only the ore sample with the highest FeO content (75 wt%) was performed (Figure 8.92). The estimated iron yield was higher (to 38%) with more than 41% iron being extracted from the ore. However, the system necessary to create this slag would need a much larger contribution from the clay (17.5%). This seems to disagree with the refractoriness of technical ceramics which could withstand high temperatures (at least 1,300°C) (section 8.3.2.1); therefore, the clay may not have contributed much to the formation of slag. All in all, and bearing in mind the limitations of an estimate based on a relatively small number of ore samples and without ash composition, the mass balance calculations support the hypothesis that relatively Fe-rich laterite (with FeO >55%) was selected for smelting, in a system where the contribution of clay was limited, and where yields were relatively high for the ore employed.

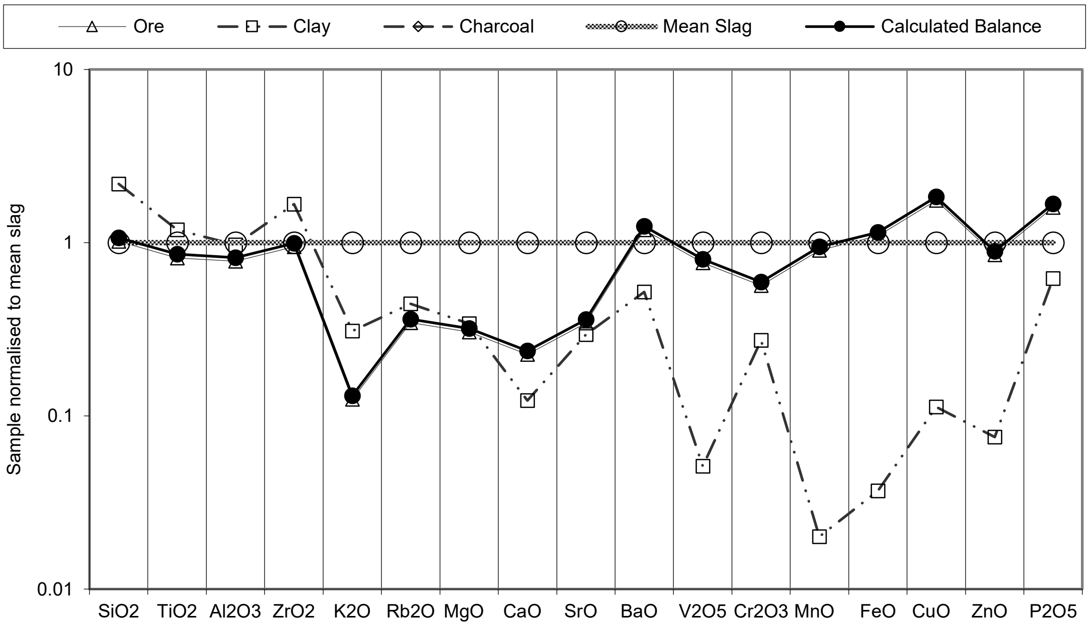


Figure 8.90 Best-fit materials balance solution for STH8 with averaged ore data. EF=1.048, 99% ore + 1% clay. A production of Fe approximately 5%, Fe Yield of some 9%.

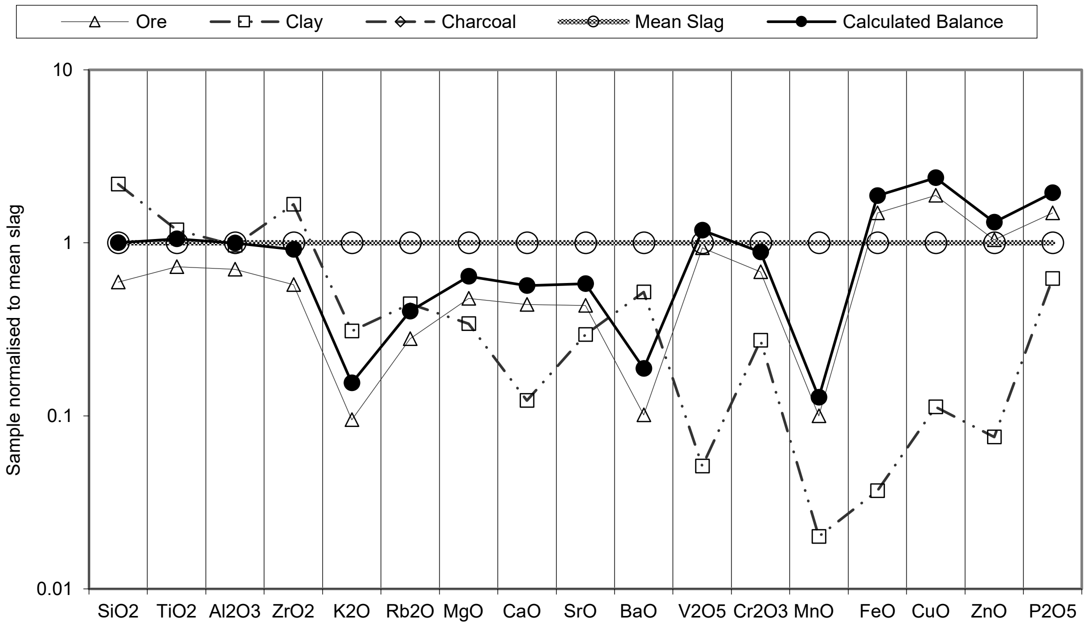


Figure 8.91 Best-fit materials balance solution for STH8 with averaged FeO-rich ore data. EF=1.373, 91.5% ore + 0.85% clay. A production of Fe approximately 30%, Fe Yield of some 36%.

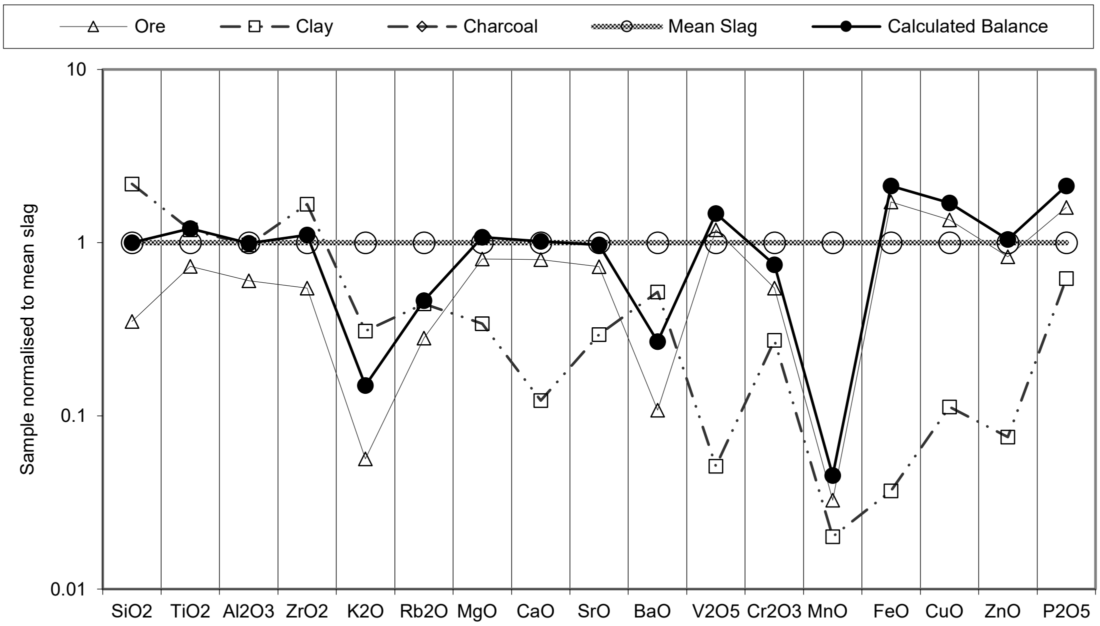


Figure 8.92 Best-fit materials balance solution for STH8 with an iron-rich laterite nodule. EF=1.49, 82.5% ore + 17.5% clay. A production of Fe approximately 38%, Fe Yield of some 41%.

8.4.1.2.3 Discussion

The above material balance calculations (Figure 8.88 and 8.90) indicate that the smelting of laterite ore of such varied chemistries could have produced slag of compositions like those recorded. This was only possible in a system that created iron-poor slag (i.e. with FeO lower than in the ore), compared to a typical bloomery slag of 55-70 wt% FeO. The calculations also showed that the laterite ore prominently contributed to the chemistry of the slag, including oxides that are often labelled as 'clay-related' (e.g. SiO_2, Al_2O_3, TiO_2, and ZrO_2). This is not surprising since, as demonstrated in the examinations of laterite samples (see section 8.3.1), their nature is very similar to that of clay with the exception that laterite also bears comparatively higher contents of iron oxides. The evaluation of the laterite strongly suggests a chemical relationship between this material as an ore and smelting slag. On this basis, the laterite likely contributed the bulk of the SiO_2 and Al_2O_3 in the slag, acting as self-fluxing ore.

There are still discrepancies that cannot be explained in full. The calculations could not provide a strong mass balance for TiO_2, MnO, CuO, ZnO, the ash-related oxides, and P_2O_5. Concerning TiO_2, in the KDT2 instance, this is likely to have derived from the ore since the clay contains less than 0.5 wt% compared to 1.5 and 1.3 wt% in the ore and slag, respectively. The STH8 instance is more blurry as all materials contains similar levels of TiO_2 (0.3-0.4 wt%), but comparison of the Al_2O_3:TiO_2 ratios of three materials (slag, ore, and clay) favours the influence of ore. MnO, as discussed earlier, was expected to be difficult to balance due to the chemical variability of the laterite samples. As this oxide is intimately associated with ore, this implies that the manganese containing laterite ore may have been smelted. This is demonstrated in Figure 8.90 that a better mass-balance fit can be achieved with the ore sample with a MnO level matching slag composition. The analysis of the laterite samples (Table 8.3) also indicated that some samples contain considerable levels of MnO. A recalculation using better representative laterite samples may clarify this issue. CuO and ZnO are also variable, and they could partition between metal and slag (or, in the case of zinc, into gas) depending on local conditions. The ash, though not analysed, is assumed to have contributed most of the ash-related oxides to the slag chemical structure, especially CaO and K_2O. The material origins of P_2O_5, which could come from both ore and ash, are harder to clarify without ash chemical data.

The above discussion also suggested that some adjustment was needed to cope with the chemical variability of the materials employed, especially the ore – both in terms of the iron content and the SiO_2:Al_2O_3 ratio. As demonstrated by Figure 8.91 and 8.92, the smelting of relatively iron-rich laterite with relatively low clay contributions would explain the slag compositions seen. The Ban Kruat smelting slag samples are chemically very similar to each other regardless of which sites they are from. Even though thermodynamics would to some extent drive the composition of the slag towards low-temperature troughs, the consistency of the slag SiO_2:Al_2O_3 ratio strongly indicates that the ore charge did not change much among smelting locales. This slag SiO_2:Al_2O_3 ratio corresponds better to the archaeological iron-rich laterite samples than to the technical ceramics, suggesting that laterites of similar grades (at least similar to FeO-rich ore specimens presented above) may have been specifically exploited among local workshops. Smelting these grades of the ore would have enabled the slag of Ban Kruat composition to form with a main contribution from the ore itself. If significant amounts of SiO_2 had been introduced as molten ceramic or flux, the slag SiO_2:Al_2O_3 ratio would be expected to be different between ore and slag (Charlton *et al*. 2010, 356). Further support to this interpretation is the fact that the technical ceramics are tested to be quite refractory, so would not contribute significantly to the slag chemistry. Interestingly, the yields estimated are quite different between KDT2 and STH8, even if FeO-rich ore samples are used for both calculations (13% vs 36%). This may be explained by slightly different furnace conditions which resulted in variable outcomes of the smelting operation. However, considering the limited sampling and uncertainties noted, any interpretation of these differences would have to be done with caution.

8.4.1.3 Reduction efficiency and iron yield obtained

Metallic iron was the desired product from the iron production in Ban Kruat. The previous section demonstrates the feasibility of the smelting system in producing iron, but the question remains about how much iron would have been produced and how efficient the process was. Here "reduction efficiency" is argued as a technical parameter (i.e. how much iron is extracted out of the iron available). However, this may not be confused with costs and benefits of the production which is culturally contingent defined by the society where the production takes place. They are also affected by various environmental and social parameters involved in the production (e.g. availability of ore, fuel, and manpower, transportation cost, prices of products, and time investment) (Costin 2001, 289-291, 2005, 1067-1068). This socially related efficiency will be considered together with the social context of Ban Kruat and lower Northeast Thailand in the next chapter.

Reduction efficiency of iron smelting can be assessed qualitatively by observing the relative proportion of free iron oxide, which can be reduced into metal, left in slag. A reducible iron index (RII) can also be used as a quantitative measurement (Charlton 2007; Charlton *et al*. 2010, 356). This is calculated via the formula $\frac{2.39 \times \mathrm{SiO2}}{\mathrm{FeO+MnO}}$, where 2.39 is the molar ratio of FeO to SiO_2 in fayalite. A RII value lower than 1.0 retains excess FeO, while the value greater than 1.0 retain SiO_2 that has not been fluxed (Charlton *et al*. 2010, 356).

Free iron oxide phases are completely absent in all samples analysed microscopically (see section 8.3.3.1.1.1), which already indicates that any iron oxides available in the system were consumed for the formation of fayalite (Fe_2SiO_4) and hercynite ($FeAl_2O_4$), and reduction into metallic iron. The high efficiency of the system is reinforced by the RII values. All 106 slag samples collected from different sites collectively show values exceeding 1.0 (1.7-2.9) (Table 8.9-8.10) corresponding to the absence of wüstite.

The high efficiency values are an indication that the smelters extracted as much iron from their ores as possible within a bloomery smelting system. This impression is strengthened by the concentration of the slag chemistry around the "optimum 1" of the relevant phase diagram, i.e. the low-iron eutectic (Rehren *et al*. 2007), as further discussed below.

This consistently high efficiency might seem at odds with the rather variable – and often low – yield values obtained in the mass balance calculations, ranging from less than 10% (KDT2) to as high as 38% (STH8 when FeO-rich ore was smelted). Some of the variability might of course reflect variable operating parameters. For example, compared to STH8, the KDT2 slag contains FeO contents about 2-3 wt% higher, meaning that more FeO was consumed by the system for slag production in the latter furnace. More generally, however, it has to be remembered that even the iron-rich laterite ores available at Ban Kruat contain less FeO than some of the typical ores smelted elsewhere. The yields from such ores are likely to be lower even if the system is efficient.

The high alumina content of the ore is also likely to have affected the yields. In other smelting systems, some compounds can replace FeO in the slag to form olivines and spinels, as is the case of CaO (as kirschsteinite ($(Fe, Ca)_2Si_2O_6$)), MnO (as MnO-rich olivine), and TiO_2 (as ulvite (Fe_2TiO_4)) (see examples in Ige and Rehren 2003, 20; Iles 2014; Iles and Martinón-Torres 2009, 2323; Lyaya 2013, 415). In the Thai case, the slag is dominated by iron-rich fayalite and hercynite, which consumed substantial amounts of iron that could not be reduced to metal.

Our limited understanding of the volume of the many slag heaps at the site, together with noted uncertainties in the calculated yields, make it impossible to estimate the amount of metal that could have been made in Ban Kruat. In any case, this smelting system was arguably effective in extracting metal from iron-poor ore and efficient in terms of the proportion of free iron oxide reduced (i.e. no excess FeO remained). However, it might not be efficient in terms of the proportion of metal produced from the mass of iron that entered the system.

8.4.1.4 Discussion: modelling smelting conditions and mechanisms for Ban Kruat iron production

With all information generated throughout Chapter 7 and 8, the following section will endeavour to explain how the slag was formed and how this can inform about the smelting conditions and mechanisms. As further discussed below, and notwithstanding small differences, the Ban Kruat slag assemblage is characterised by its internal coherence and similarities – which renders this broad, generalising discussion justifiable. In short, all the slag is high in alumina and low in iron and, arguably, ash oxides, with its chemistry dominated by ore oxides.

Reconstruction of smelting condition

By working with alumina-rich laterite ore, Ban Kruat produced slag that was high in alumina (14-16 wt%), much higher than most typical fayalitic slag (below 6 wt%) (Tylecote 1987; Pleiner 2000, 252; Paynter 2006, 2007; Rostoker and Bronson 1990, 91; cf. Humphris 2010; Lyaya 2013). When the reduced data are plotted on the FeO-SiO_2-Al_2O_3 phase diagram, the slag is clearly associated with the “optimum 1” region (Figure 8.93). As discussed by Rehren *et al*. (2007) and Charlton *et al*. (2010, 356-357), the composition of bloomery iron slag tends to cluster around one of two eutectic or “optima”, where fayalitic slag can be produced in the lowest possible melting temperatures, minimising the heat energy consumed and facilitating the separation of metal and slag. The low-iron “optimum 1” is usually associated to a highly reducing atmosphere generated by increased fuel:ore ratios, resulting in an increased iron yield. This comes with a higher risk of the smelt failing, as this eutectic is surrounded by rather steep thermal gradients (and hence slag can easily become more viscous or freeze). The system is also prone to producing cast iron because of the excess carbon monoxide, and more iron can be trapped in slag due to viscosity. This is in contrast to “optimum 2” which operates in lower fuel:ore ratios; however, in return, excess FeO is left unreduced, and comparatively lower yields of iron are expected. The separation of iron from slag is likely to improve as a more fluid slag can be created. Operating the furnace around either optimum 1 or 2 can be technologically advantageous or disadvantageous depending on the context: in any case, it can reflect the broader set of environmental or economic contraints affecting smelting practice. Although these temperature minima are largely driven by the thermochemical behaviour of the three main oxides, furnace operation as revealed through this approach can also reflect human choices as well as cultural and technical variation.

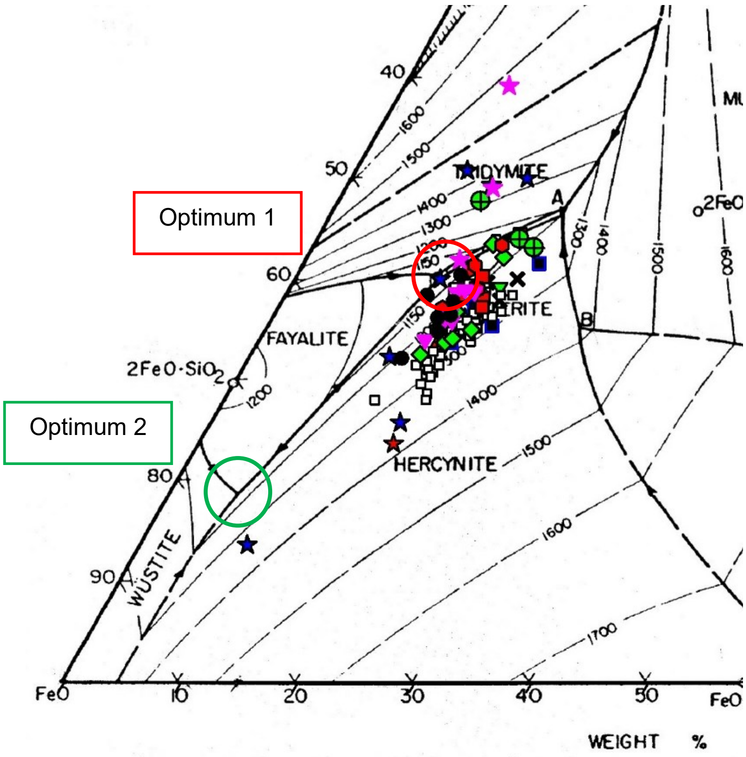


Figure 8.93 Ban Kruat smelting slag (other symbols) and laterite samples (stars) on the FeO-SiO_2-Al_2O_3 diagram, shown only the FeO corner of the diagram. Two optima mentioned are marked by red and green circles. See Figure 8.65 for the full diagram.

Interpreting Ban Kruat smelting conditions in this light, the optimum 1 is argued to be the a strict condition that allowed iron to be extracted from the ore overall poorer in FeO compared to typical iron ores (e.g. magnetite and haematite) (cf. Rehren *et al*. 2007, 214). High-FeO-containing iron ores, when smelted, allow the smelting system to be operated flexibly between two optima, depending on the furnace configurations set (see Charlton *et al*. 2010 for a change of the recipes using the same ores). However, when a poor ore is smelted such as in the instance of Ban Kruat, the system needs to be configured in order to harmonise with low FeO. The operation of a furnace such as those at Ban Kruat in the optimum 2 would not be possible with the ores available, as all FeO would be consumed by silica and other compounds, including alumina, to form slag and leave none to be reduced to metal. The only potential alternatives were either introducing richer ore to increase FeO contents in the system (if such ores were available) or operating the furnace in the optimum 1 condition. The analytical interpretations of ore and slag in Ban Kruat favour the latter solution, while the possibility of ore selection to favour the less-poor ones cannot be completely rejected. By operating the furnaces at this minimum temperature, iron could have been extracted from the laterite ore while slag was produced. This is demonstrated by the materials balance above.

It may now be possible to further speculate about the redox environment within the furnaces. The identification of a few cast iron inclusions trapped in the slag support the hypothesis of very high-carbon iron as the risk associated to operating the furnace in this optimum. Relatedly, a relatively high fuel:ore ratio was presumably employed to achieve a more strongly reducing atmosphere facilitating the better reduction of FeO. The abundant round porosity in much of the slag are also consistent with a system rich in carbon monoxide.

To complete the reconstruction of the smelting technology, the characteristically high alumina nature of the ore needs to be taken into account, as another important constraint that explains Ban Kruat smelting had to be operated in this manner. As discussed above, high alumina causes a major problem as it increases melting point and viscosity of slag. According to the diagram (Figure 8.93), the laterite ore samples, particularly those FeO-rich samples (and correspondingly lower SiO_2:Al_2O_3 ratios), required temperatures around 1,200-1,350°C, which could have been reached by Ban Kruat furnaces as indicated by smelting slag. Maintaining the temperature of the smelting in the range of the liquidus temperature of Ban Kruat smelting slag (as high as 1,300°C at least) was therefore also a crucial requirement. This was necessary to prevent the early crystallisation of alumina-rich phases that might halt the smelting operation. As visible in the FeO-SiO_2-Al_2O_3 diagram, the temperature window around the optimum 1 is very narrow (Figure 8.93); therefore, temperature control was critical.

Up to this point, it has been proposed that a high fuel:ore ratio would have been required to ensure the high temperatures and reducing conditions required. This, however, might seem at odds with the relatively low levels of ash-related oxides, particularly CaO (1-2 wt%), K_2O (0.3-0.6 wt%), and P_2O_5 (0.2-0.4 wt%) in slag. As noted previously, it was very difficult to find charcoal inclusions in the slag, and these were always very small (less than 0.5cm), which suggests that the bulk of the charcoal fuel was consumed during the operation. At the same time, we lack evidence about the nature of the fuel employed, its composition and ash yield. In any case, an important parameter to explain this apparent contradiction is the Boudouard reaction, which dictates that the free energy of formation of CO decreases with temperature. As established above, the Ban Kruat furnaces were operated at temperatures considerably higher than typical bloomery systems; hence, the redox environment would inevitably be more reducing. This could well have been facilitated by adjustments to the air supply system rather than simply by increasing the charcoal:ore ratio.

Modelling the mechanism of iron production

The modelled smelting condition in conjunction with the macro and microstructural characteristics of ore and slag samples allows the mechanism of the smelting process to be illuminated. While the microstructural analysis of the slag samples did not reveal every detailed reduction processes, as described by Blomgren and Tholander (1986) or Killick and Gordon (1989), an illustration of the iron reduction process in Ban Kruat context can still be conveyed, though still limited, by the slag collections.

The charge consisted of the laterite ores, which contained mainly hydrated iron oxide in a gangue of quartz and alumina-rich materials soil, and charcoal as a fuel. The iron oxide could be concentrated as pisoliths, either bound together into a lump by clay/quartz materials or varyingly dispersed across the quartz-rich groundmass (see section 8.3.1). The permeability of the iron oxyhydroxides likely facilitated the penetration of the furnace gases through the structures of the ores (Killick and Gordon 1989, 120). As the reaction progressed, the quartz grains and alumina-rich material continuously reacted with iron oxide to form fayalite and hercynite. The slag block samples exhibit the formation of new phases as quartz reacted and dissolved into the matrix (see section 8.3.3.1.2). Incompletely reacted or unreacted quartz regions were observed in some samples but not as a dominant region. Rather, the overall homogeneous microstructure of slag implies that the charge was well reacted, transforming into a viscous iron-alumina-silicate (see section 8.3.3.1.1.1). This reaction took place at 1,200-1,300°C or slightly higher (see section 8.4.1.1.1).

Based on the inferences by Blomgren and Tholander (1986) or Killick and Gordon (1989), who observed metallic grains as pseudomorphs of parent ore or wüstite grains, we can further hypothesise the smelting mechanism. However, it should be noted that the absence of such relict structures in the Ban Kruat slag suggests perhaps a slightly different smelting mechanism, or at least one that, perhaps owing to the higher temperatures, removed iron more efficiently from the system. Iron oxyhydroxide was possibly first dissolved in the slag after the charge melted. It would then precipitate as free iron oxide within the slag. The overall globular shape of metal indicates that excess carbon, also indicated by abundant gas pores in slag, was available to promote a carburisation of metal (Figure 8.50), sometimes leading to accidental cast iron fragments (Figure 8.55-8.59). Some of the metallic particles, although very rare in the samples analysed, still retain the shapes of the wüstite dendrites (Figure 8.51). The slag samples illustrate the aggregation of smaller prills into larger ones (Killick and Gordon 1989, 121) (Figure 8.53 and 8.54). There is also the possibility that iron was formed through a direct reduction from the ores, as suggested by iron particles trapped in quartz-rich regions. These are interpreted as remnants of the ore structure, where the iron oxide contained within was reduced into metal but remained trapped and could not join the bloom (Figure 8.63).

The resultant slag from the complete process was exceptionally lean (i.e. without free iron oxide), consisting of new formed phases and, occasionally, unreacted quartz (see section 8.3.3.1.1.1). High alumina in the slag made it unavoidably viscous. It is possible that, at the beginning of the slag formation, the slag created might not be as viscous as the final slag; however, as more iron oxide was progressively consumed or reduced, the viscosity was subsequently higher. This posed a major challenge for slag removal, escaping of gases, and bloom formation. The relatively high viscosity of slag (approximately 5-6 poise) would make it more difficult to drain it out of the furnace; this is clearly demonstrated by the fact that none of slag lumps exhibits flow textures, a common feature of tapped slag but even in some furnace slag (see section 7.3.2.1). It is clear that the slag was not tapped – contrary to previous suggestions (see section 7.2.4.1. However, its microstructure indicates a relatively fast-cooling process (e.g. elongated fayalite crystals and underdeveloped and non-equilibrium phases) (see section 8.3.3.1.1.1). Thus the method of slag removal possibly involved mechanically forcing it out as small lumps, exposing them to cooler air. This explains macroscopic appearance of Ban Kruat smelting slag that are usually found as lumps (see Chapter 7). Even if slag remained within the furnace, given its high melting ranges it is likely to have solidified as soon as the operation was halted and the temperature dropped. The gases within the slag could not escape the viscous structure and, subsequently, created voids.

The low FeO content of the ore required high-temperature and highly reducing smelting conditions in order to completely suppress the formation of free iron oxide. The yields of iron could have been varied, but it is certain that they were collectively affected by the fact that a relatively large amount of FeO was consumed by silica and alumina to form the necessary slag. It was suggested that relatively higher consumption of fuel must have been necessary for the success of the system, though it was acknowledged that this seems at odds with the relatively low levels of ash-related compounds in slag.

The inferences about viscosity based on the chemical analysis, as well as the microstructure of slag, clearly demonstrate the difficulty for iron particles to travel and coalesce in a bloom. Slag was unlikely to flow fluidly during smelting, and a solution may have been the push the system towards the optimum 1 region. The progressive addition of carbon in iron decreases the melting temperature of the metal to much more manageable ranges (from 1,537°C of pure Fe to as low as 1,143°C with 4.3% C). Most metallic remainders in slag appear in the forms of prills, indicating that they are at least partly molten and with the smallest surface area relative to volume. This would have make it easier for the metal to travel through the viscous slag.

The last aspect to be discussed, and arguably one of the most important, is the final product. As aforementioned, iron was produced in a carbon-rich system, as inferred by the presence of carbon-rich metal prills with iron pseudomorphs of the wüstite rarely seen, the abundant porosity (CO bubbles), and the lack of free iron oxide. Thus the iron produced was most likely carbon-rich, and the highly reducing atmosphere may also encouraged elements (e.g. phosphorus, vanadium, chromium, arsenic, and silicon) to bond with carbon-iron alloys as trace elements, also affecting the properties of the resulting metal. Phosphoric iron prills are also present probably as a result of this smelting system. The direct production of steel could generally be seen as advantageous, but the risk was high, as indicated by the formation of phosphorous-rich cast iron, which would be useless if decarburisation methods were not known.

Furthermore, although the evidence points to the production of high-carbon iron, this may not be an intentional outcome of this system but rather an unavoidable accident. Importantly, low-carbon ferritic iron was also identified too, indicating that some areas of the furnace were less reducing or not saturated by excess carbon. The slag viscosity would also hinder a uniform distribution of reducing gasses. According to the Fe-C diagram (Figure 8.52), at proposed smelting temperature of 1,300°C, iron would need about 3% C to be fully molten; however, assuming that reducing gasses would struggle to travel through the viscous slag and the prills are only semi-liquid, it can be argued that the bulk of iron produced would not absorb this much carbon, thus not being high-carbon iron. Cast iron would only be an occasional accident. On this basis, it can be postulated here that the smelters would produce a bloom with uneven distribution of carbon across the iron body. A variety of iron (soft iron, steel, and cast iron) might have been present in the different parts of the bloom.

The direct production of steel in a bloomery furnace is generally considered a rarity; although, it is possible to achieve high-carbon iron by “high bloomery smelting” (Tholander 1987) and in other exceptional cases (Craddock 2003; Crew *et al*. 2011; Navasaitis and Selskienė 2007). Ban Kruat may constitute another case where mild steel could have been produced directly from the bloomery smelting without a separate stage of carburisation, but experiments are required in order to test this proposition.

Some note also needs to be made regarding the smithing of the bloom. It is worth mentioning that steel has the ‘disadvantage’ that it is much harder to smith, therefore it is only desirable if the objects to be made necessitate the properties of steel. Due to the viscosity of slag, it is highly likely that the bloom created would be full of slag, probably in higher quantities than in ordinary ferritic blooms with fluid slag. It is therefore reasonable to infer that a long session of bloom consolidation by hammering would have been needed. An extra step of refining (i.e. removal of impurities in iron or decarburising/lowering carbon content in cast iron and high-carbon steel to workable iron) might be of use in some instances, but no evidence for this has been found.

8.4.2 Technical variability in Ban Kruat iron production: assessing similarity and change in local smelting tradition (recipe)

Like in many other areas of archaeology and technology studies, many archaeometallurgical studies on iron production remains focus on identifying and explaining variation (e.g. Childs 1991; Charlton *et al.* 2010; Iles 2011, 2014; Juleff 2009; Pleiner 2000; Rehren *et al*. 2007). On the one hand, remarkable conservatism or persistent technology has been presented as characteristic of some production areas (e.g. Lyaya 2013; Paynter 2006). On the other hand, some production areas have been related to technological variation and change in practice over periods of time (Bray 2006; Buchwald 2005; Charlton 2007; Humphris 2010; Iles 2011, 2014; Joosten 2004). When a particular iron smelting practice has been transmitted and repeated over extended periods of time, it can be considered a tradition (patterned way of doing thing) or recipe (transmitted information about how to produce something) (O’Brien *et al*. 2010). This tradition/recipe is subject to adaptation, modification, and copying errors which are intimately linked to environmental (e.g. smelting ingredients, components, and conditions) and socioeconomic and cultural setting (e.g. craft specialisation, political organisation or market pressures). Technological variation results from in tradition/recipe, and this can be stimulated by a wide range of factors (Eerkens and Lipo 2005, 2007; O’Brien *et al*. 2010).

The study of nearly 50 slag deposits around Ban Kruat enables this research to pursue research along these lines, assessing to what extent local technology is persistent or subject to variability and change. However, there is one issue to be remembered. A lack of overall chronological resolution for metallurgical activities does not permit this study to discuss change on a diachronic line. Instead, this study only seeks to identify any indications for changes and variation in smelting traditions or recipes, if any, to be further explained when more detailed chronological data becomes available in the future. A diachronic investigation is only possible for KDT2, which is dated and yields stratified materials.

An assessment of variability within and between workshops also allows to tackle issues of quality control and standardisation. To what extent were local smelters able to control or replicate the operational procedure time and time again? How standardised was the procedure between workshops? The issue of standardisation can be used further for investigating the nature of organisation, and probably political economy, of craft production in particular societies (Costin 1991, 2001, 2005; Costin and Hagstrum 1995; Li *et al*. 2014; Martinón-Torres *et al*. 2014; Stark 1995). This enables the elucidation of the development and place of specific craft production in the political economy of the societies (Sinopoli 2003; Smith 2004). These dimensions will be discussed in the next chapter which, returns to the socioeconomics of production, but it is necessary to identify and characterise variation first.

In light of this, the exploration of smelting slag samples in terms of their structures, key oxides (Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2, MnO, and FeO), *F*-value (tracking change in ore selection (Buchwald 2005; Charlton 2007, 157; Charlton *et al*. 2010, 356)), and RII (tracking change in furnace operation (Charlton *et al*. 2007, 356)) was done first to identify groups, which could represent different recipes or traditions, changes, and variation. Coefficients of variation (CV) was also calculated for the bulk chemical data of all smelting slag samples (see Table 8.9-8.12) in order to obtain another quantitative proxy for variation and standardisation (Eerkens 2000; Eerkens and Bettinger 2001; Illes 2011; Li *et al*. 2014; Martinón-Torres *et al*. 2012; Stark 1995 and Pryce *et al*. 2010; Pryce *et al*. 2014 for local applications of this approach to archaeometallurgical remains).

The analytical results have so far allowed the identification of two broad slag groups (western and eastern group) based on the differences in the size and weight of the slag lumps (Figure 7.74-7.77) and their chemical composition (TiO_2) (Figure 8.69). However, outside these two indicators, no further subgroups can be easily discerned, as shown by plots of smelting slag in the FeO-SiO_2-Al_2O_3 diagram (Figure 8.65-8.68). The fairly consistent slag SiO_2:Al_2O_3 ratio (*F*-Value) strongly suggests that the ore smelted was similar across the sites (Figure 8.94). RII values show that the reduction efficiency is very similar at all studied sites (above 1.5) (Figure 8.95). These indicators imply that there may have been no significant difference or change in a tradition or recipe used to extract iron across the area. Nonetheless, CVs of both values are more variable for some sites than others. The variation of *F*-Value is possibly related to the different levels of absorption of SiO_2 and Al_2O_3 by some slag samples (e.g. closer to technical ceramics or chemical heterogeneity of the ore). The variation of RII is likely to be due to the incorporation of some smelting slag samples with higher MnO levels, probably implying the use of MnO-containing laterite ore.

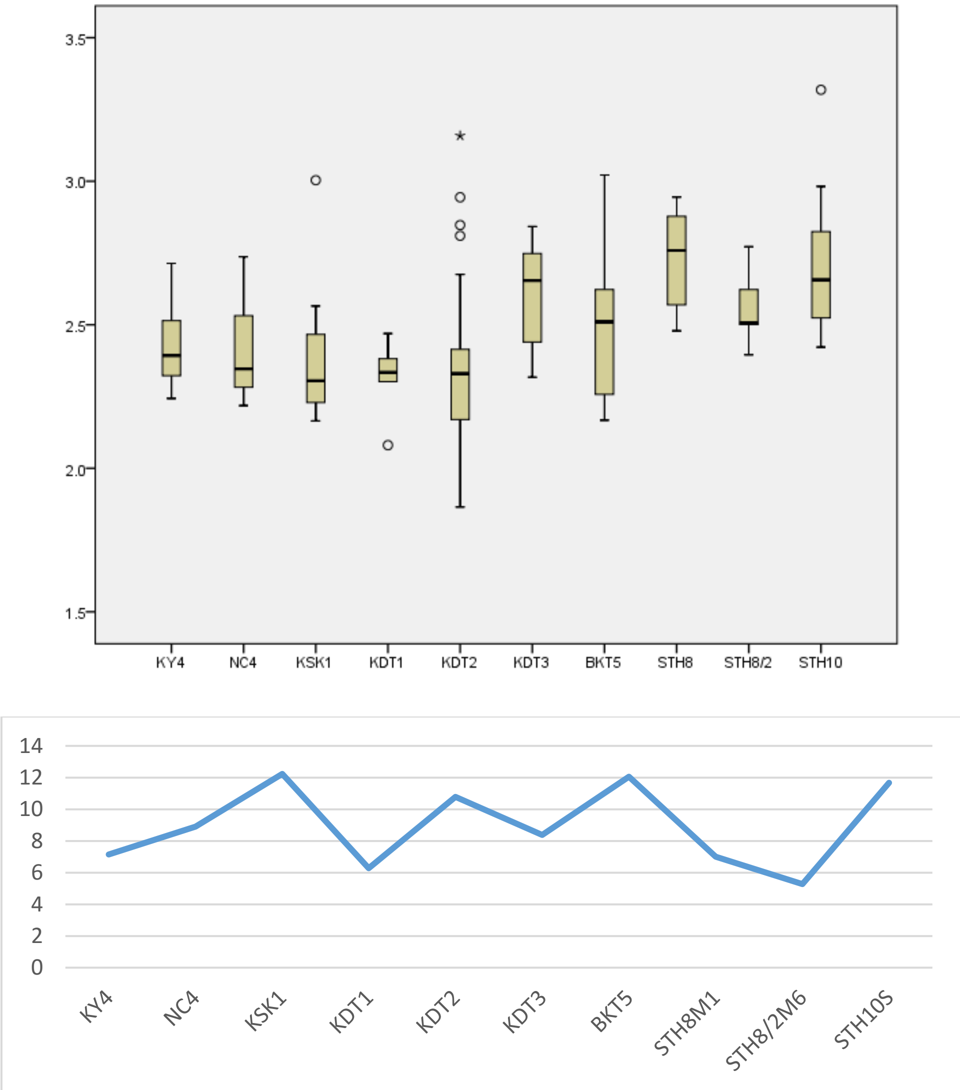


Figure 8.94 F-values boxplot intended to provide a non-parametric summaries of the measured values and CV of the values, calculated from the WD-XRF chemical composition of the smelting slag from each studied site.

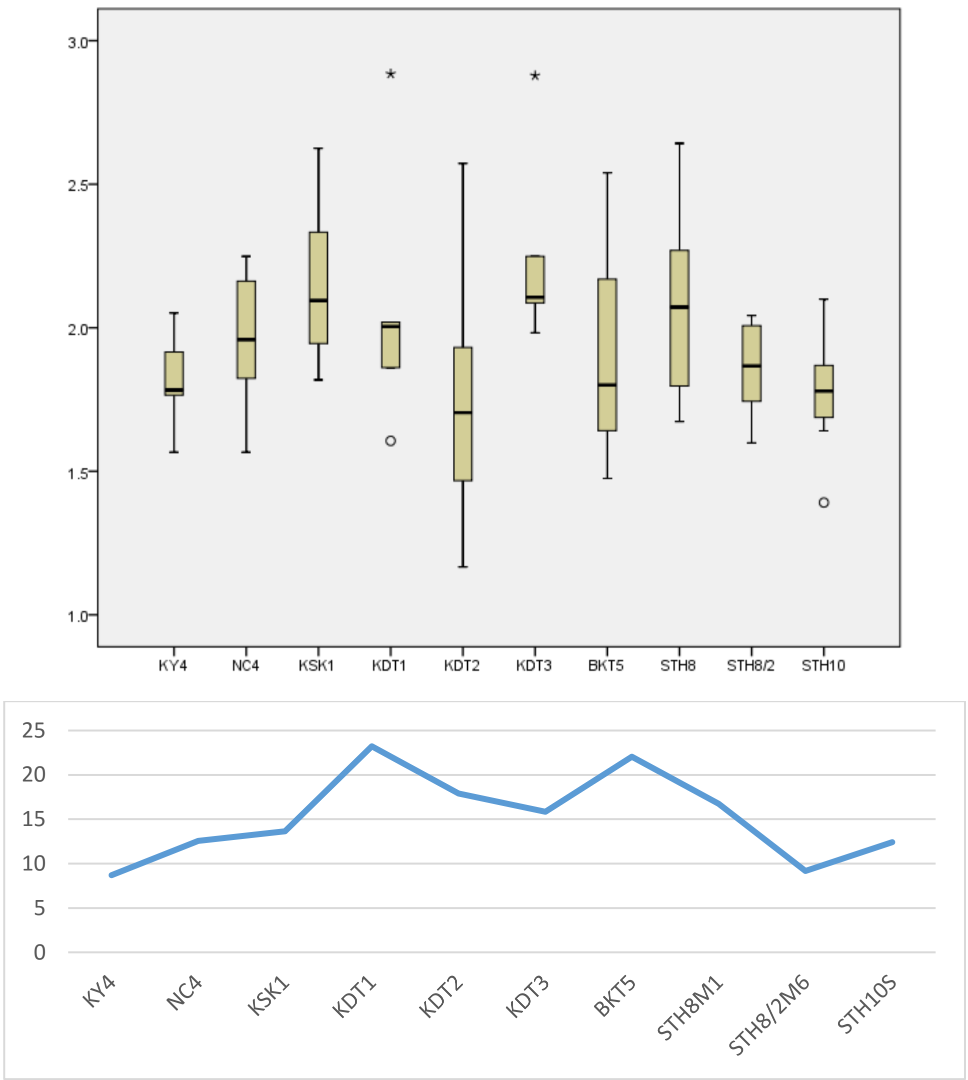


Figure 8.95 RII boxplot and CV of the values calculated from the WD-XRF chemical composition of the smelting slag from each studied site.

8.4.2.1 Groups and variability between slag deposits

To further investigate any possible groups in the smelting slag assemblage, PCA in conjunction with hierarchical cluster analysis, employed to better explore the PCA result, was undertaken on the slag chemical data (see the setting for each analysis in Appendix L). For the following explorations, only particular oxides were included for this multivariate analysis. Key oxides including SiO_2, TiO_2, Al_2O_3, P_2O_5, K_2O, CaO, MnO, and FeO were considered for their correspondence to parent material. SrO, ZrO_2, and BaO, though having high errors, were also included for their relationship with both ore and clay (see section 5.3.3.2). These oxides were hoped to help identify any chemical variation within slag samples.

As previously observed, the samples are largely divided into two groups: a-e and f-h, which respectively represents western (a-e/KY4, NC4, KSK1, KDT1-3, and BKT5) and eastern groups (STH group) (Figure 8.96). The western group, though dispersed across the upper part of the graph, tends to be richer in, for example, TiO_2, P_2O_5, CaO, and SrO and depleted of SiO_2 and several minor oxides. Two subgroups (red and blue) can be observed in this group where the blue group seems to contain higher P_2O_5 and FeO. The eastern group appears to show the reverse. There is also some overlap between two groups, particularly the distribution of the STH8 samples that move into the western group zone. The main outliers, clustered on the right side of the graph, are the samples that contain higher levels of MnO and BaO or CaO thus being separated from the others. They were then removed to improve the result of other calculations below.

Despite a recalculation of the western group, which comprised of most slag clusters in Ban Kruat, without other samples, the result remained very similar to the previous one (Figure 8.96). Despite an overlap of most samples, some samples from KY4, NC4, KSK1, and BKT5 form a weak group on the upper left corner of the graph. Lastly, the calculation was performed on the KDT group, hoping to examine if the different smelting behaviours within the same cluster may have existed. The result revealed a separation between KDT1 and KDT3, while the KDT2 samples disperses across the graph (Figure 8.98). Nonetheless, the patterns seen might be because of smaller sample sizes of KDT1 and KDT3 which could be changed by increasing the sample numbers.

This separation of these groups can be explained by various reasons, including the sample sizes, more absorption of CaO and P_2O_5, likely from fuel ash, and BaO, from the technical ceramics, by some slag samples, and the heterogeneity of the laterite ores used. From all observations so far, the variability of the ore chemistry seems to be the main influential factor creating the subgroups. Its heterogeneity has already been noted; while alumina remains generally high, other oxides associated with the ore vary, including MnO and TiO_2 (see Table 8.3 and 8.4). The TiO_2 levels in the ore and smelting slag samples in each subgroup (western and eastern) seems to support the effect of the ore bodies on the variation (Figure 8.96 and 8.99). The levels of MnO also vary considerably across the samples regardless of the sites; however, no clear pattern can be observed from the PCA calculations. This observation further implies that each group had access to different ore bodies, one rich in MnO or TiO_2 than the other.

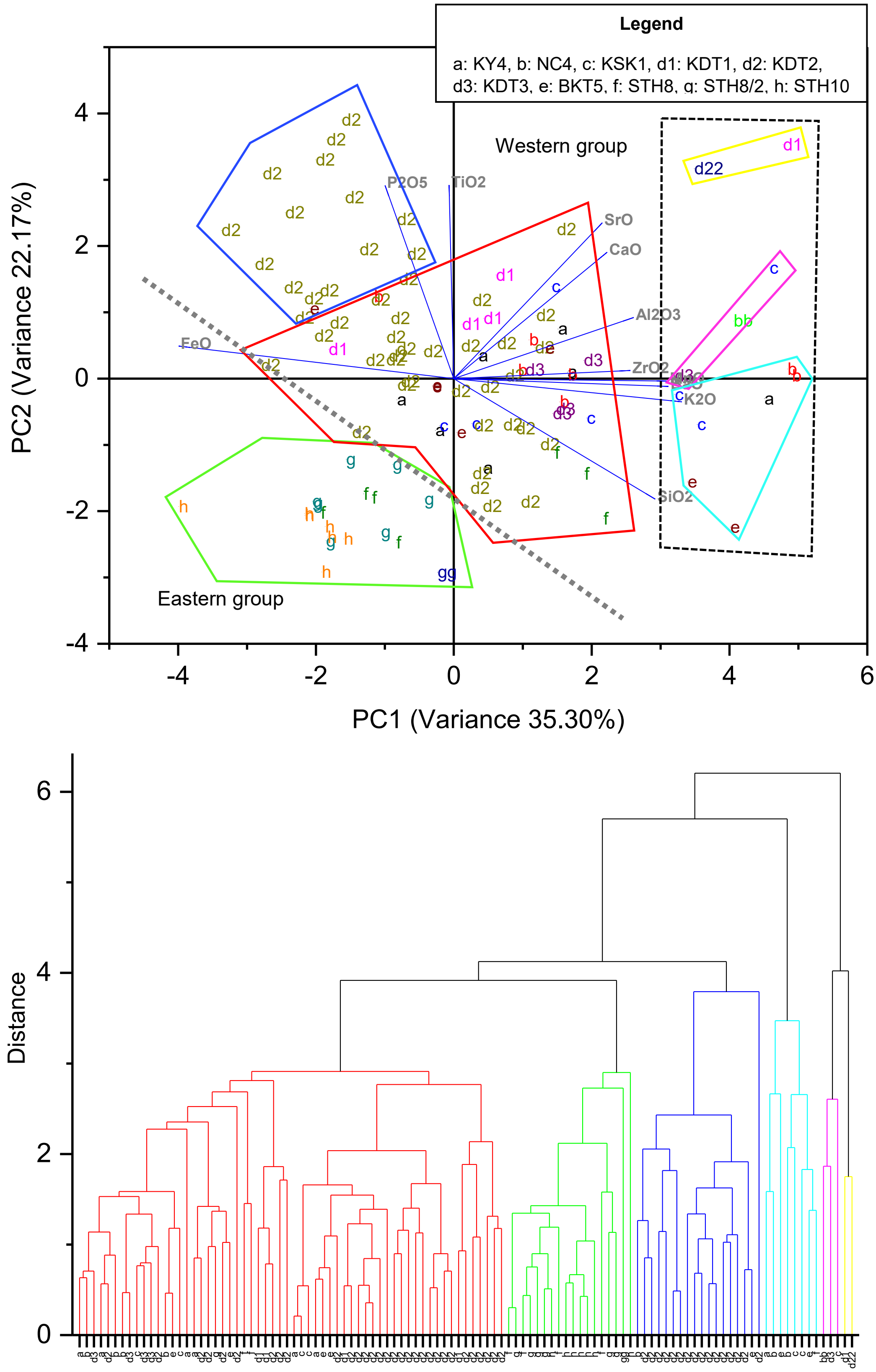
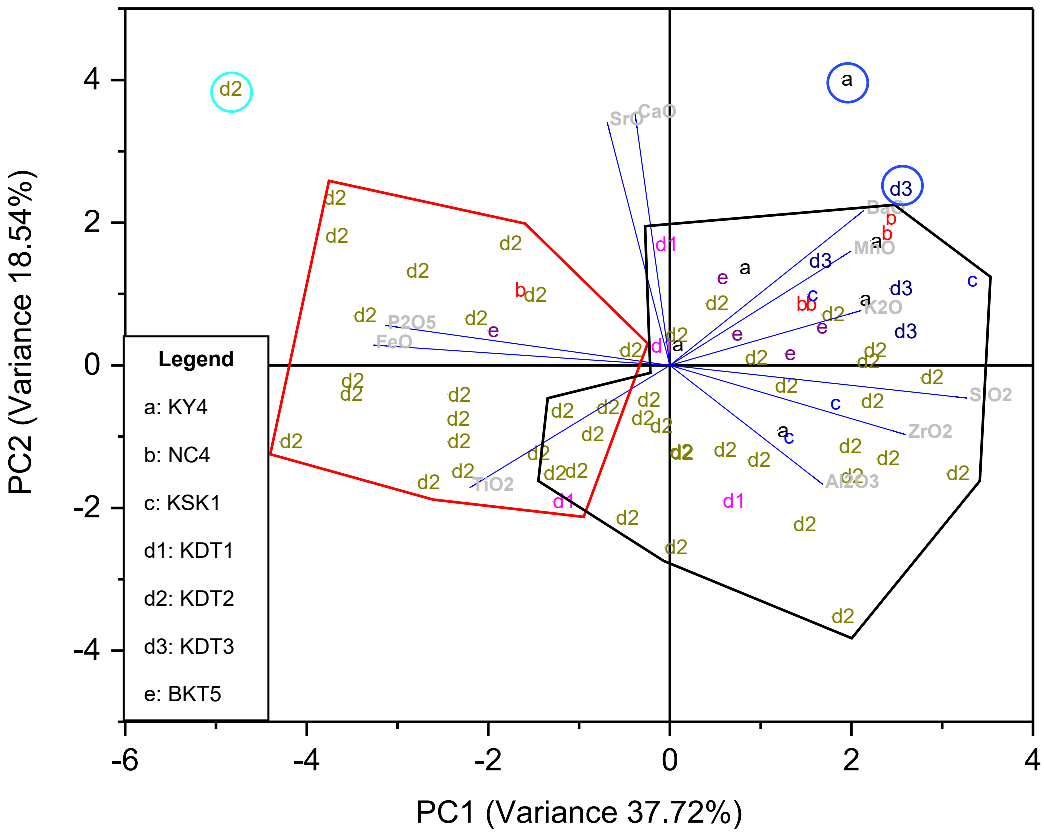


Figure 8.96 PCA plot for smelting slag chemistries from studied sites (PC1 VS PC2) (first three components explain 72.10% of cumulative variance) (above). Group identification was done using hierarchical cluster analysis of PC scores with eigenvalue greater than 1 (PC1-4) (below). The dashed box represents outliers.



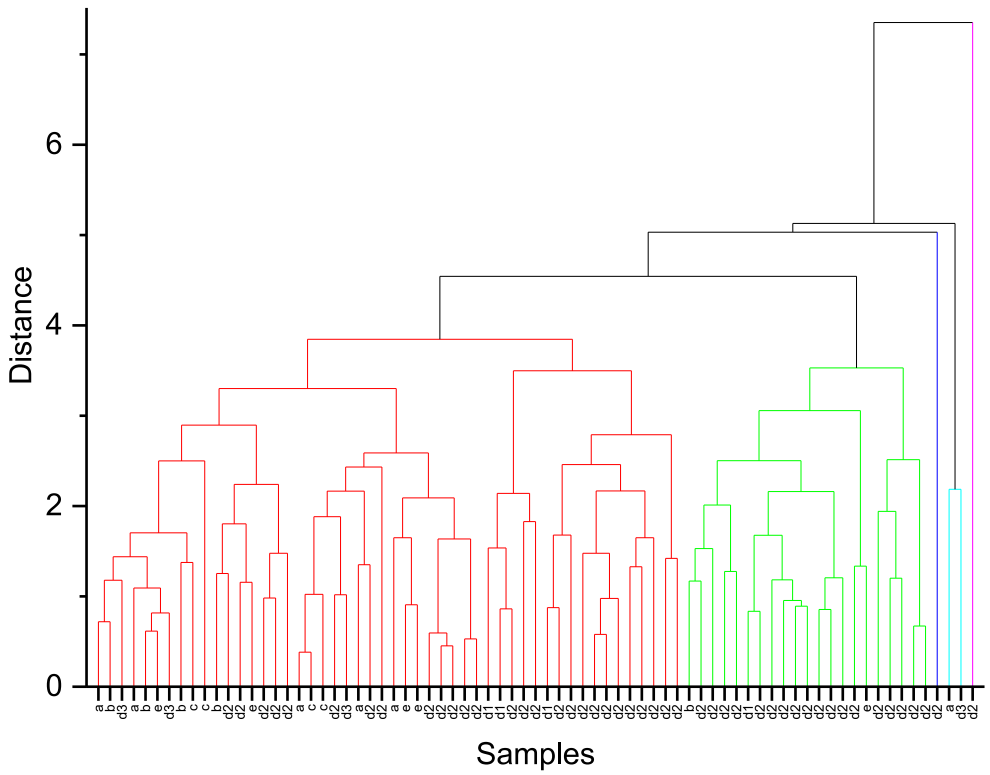
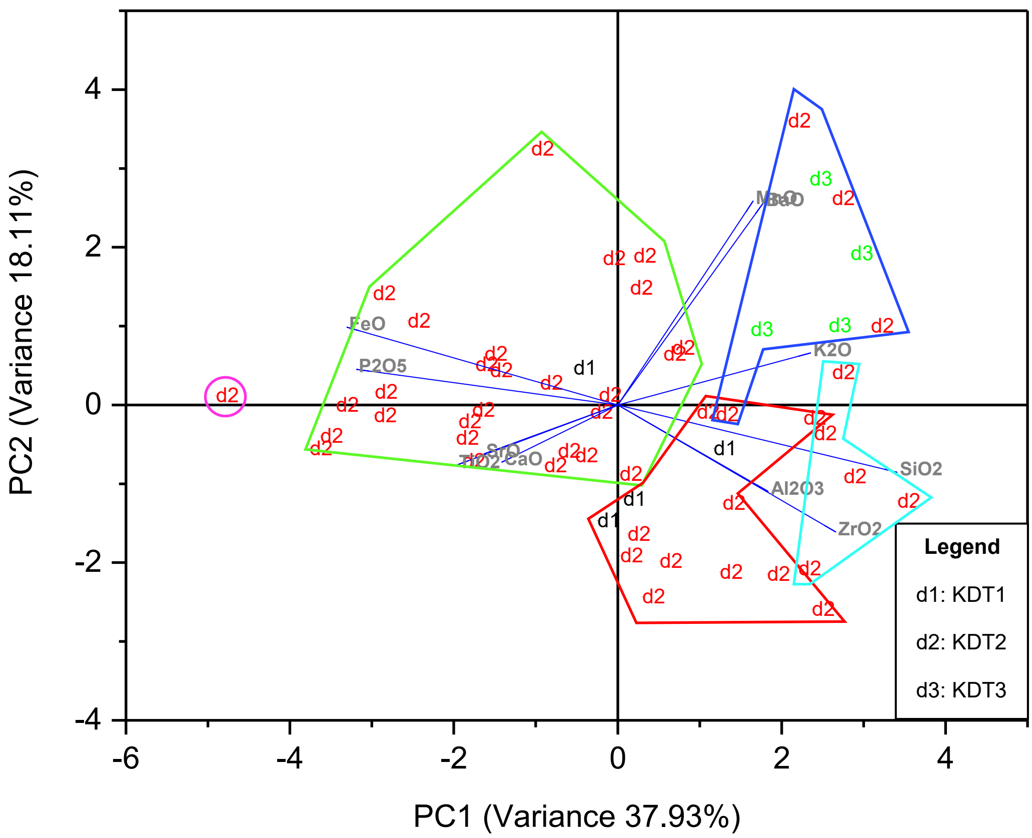


Figure 8.97 PCA plot for smelting slag chemistries from the western group (PC1 VS PC2) (first three components explain 72.53% of cumulative variance) (above). Group identification was done using hierarchical cluster analysis of PC scores with eigenvalue greater than 1 (PC1-4) (below). Outliers tend to contain either high levels of MnO and BaO (blue) or low Al_2O_3 (cyan).



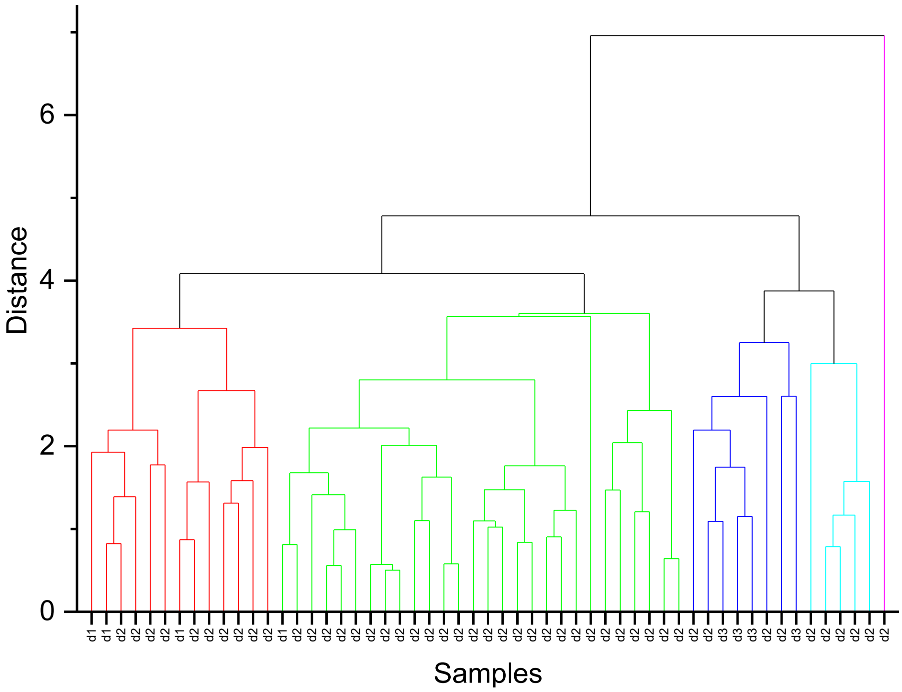


Figure 8.98 PCA plot for smelting slag chemistries from KDT1-3 (PC1 VS PC2) (first three components explain 72.59% of cumulative variance) (above). Group identification was done using hierarchical cluster analysis of PC scores with eigenvalue greater than 1 (PC1-4) (below).

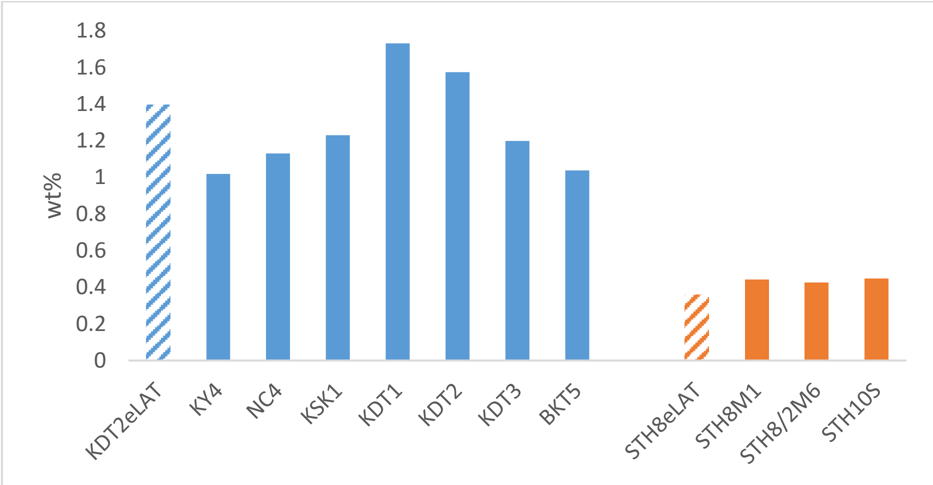


Figure 8.99 A comparison of averaged TiO_2 content between the ore sample (patterned) and slag samples (solid) in each subgroup: western (blue) and eastern group (orange)

Despite the existence of subgroups, there seems to be no indication of significant changes in technological processes or raw materials within the studied sites, and the smelting practices appear to have been very similar across the landscape of Ban Kruat iron production.

Having established that similar smelting technologies were followed in all workshops, it is possible to further assess variability of the operation carried out within each workshop. There are several challenges for this approach. The first one is that we are using variation in a by-product as a proxy for variation in practice (and, by extension, in the product); the second one is that we lack experimental references or benchmarks that would allow us to state what can be considered 'high' or 'low' variability. As such, we can only produce relative comparisons between the sites examined, which are supplemented with comparisons to slag from other sites where laterite smelting has been proposed.

From the boxplots of key oxides (Figure 8.100-8.110) and the CV calculations for all studied smelting slag (Figure 8.111), the three dominant oxides (FeO, SiO_2, and Al_2O_3) remains very steady, below 10% overall for all studied sites. Other oxides stand out as showing much higher variation. Again, apart from the groups suggested by TiO_2, there is no obvious pattern that would allow us to discern any one smelting locale as more or less standardised than another. When compared to CVs calculated from published data of other laterite-related smelting sites (Figure 8.112), interestingly Ban Kruat shows comparatively lower variation in SiO_2 and Al_2O_3, while other oxides show similar degrees of fluctuation.

The similar CVs for the dominant oxides among the Ban Kruat sites suggest a characteristic approach to smelting engineering that led to controlling the relative proportions of the main components in the slag. This is consistent with the also comparable structures and chemical compositions of smelting slag that were found across the Ban Kruat landscape. The exploration of variation also could not discern any different traditions, emphasising that the iron production in Ban Kruat was constructed upon very similar traditions.

It was demonstrated earlier that Al_2O_3 and SiO_2 were associated mainly with the laterite ores and essentially influenced the way the furnace was operated. Owing to this, local smelters seem to have empirically focused on controlling these three oxides more than others, which in return ensured the creation of desired iron. The selection of FeO-rich ore pieces may have been a crucial process to achieve this comparable smelting practices (at least for these three crucial oxides). On the one hand, this ensured that there was enough iron in the system to produce a bloom. On the other hand, bearing in mind the correlation between FeO levels and Al_2O_3:SiO_2 ratios in the laterite shown above, the use of iron-rich laterite would also reduce variability in the composition of the smelting charge.

Other oxides were likely to be more difficult to control, but their relatively small concentrations mean that they likely had very little influence in the actual practice of success of the smelt. The high variation of MnO indicates a heterogeneity of the ore bodies, even within the same area (i.e. there is a variation detected within the same spatial group); the variation of TiO_2 is lower suggesting less diversity of this oxide within ore bodies, and only two ore bodies have been detected so far (i.e. TiO_2-rich and TiO_2-poor). High variation of ash-related oxides (K_2O, P_2O_5, and CaO) may suggest that there were constant adjustments of fuel:ore ratio in order to meet the requirements of the recipe or, possibly, the exploitation of different local woods for charcoal making. There is also a possibility that different clay sources were exploited for making technical ceramics as indicated by high variation of clay-related oxides (ZrO_2, SrO and BaO) Overall, the evidence discussed here may be taken as evidence for relatively controlled beneficiation and smelting process, which allowed smelters to cope with the chemical diversity of the laterite ore.

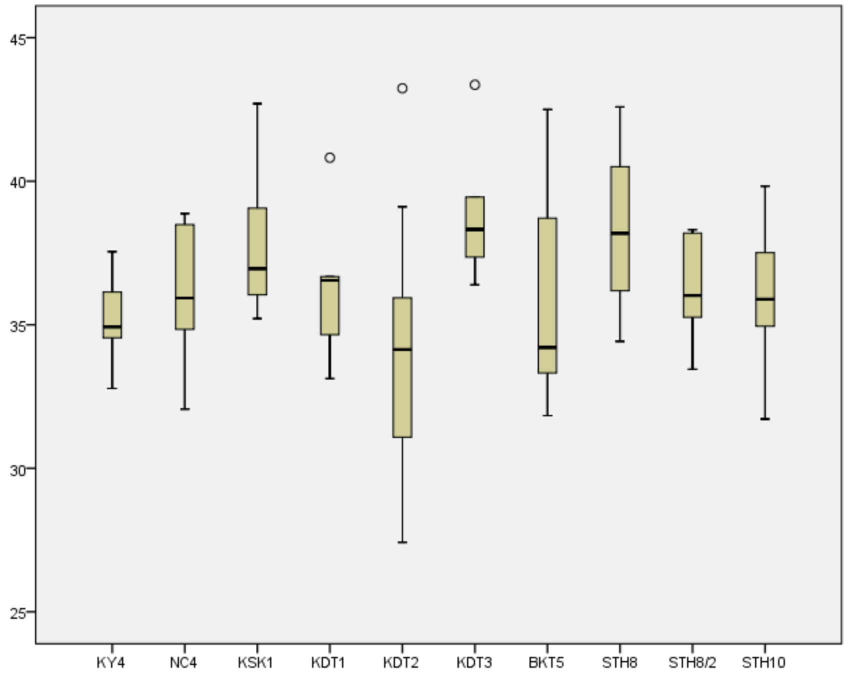


Figure 8.100 The boxplot shows the levels (wt%) of SiO_2 in the smelting slag across the studied sites

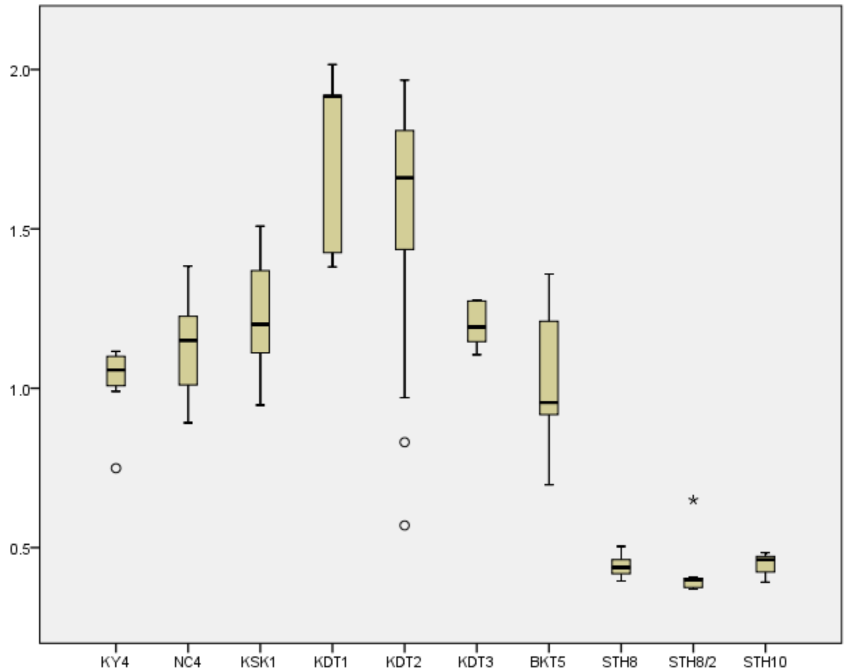


Figure 8.101 The boxplot shows the levels (wt%) of TiO_2 in the smelting slag across the studied sites

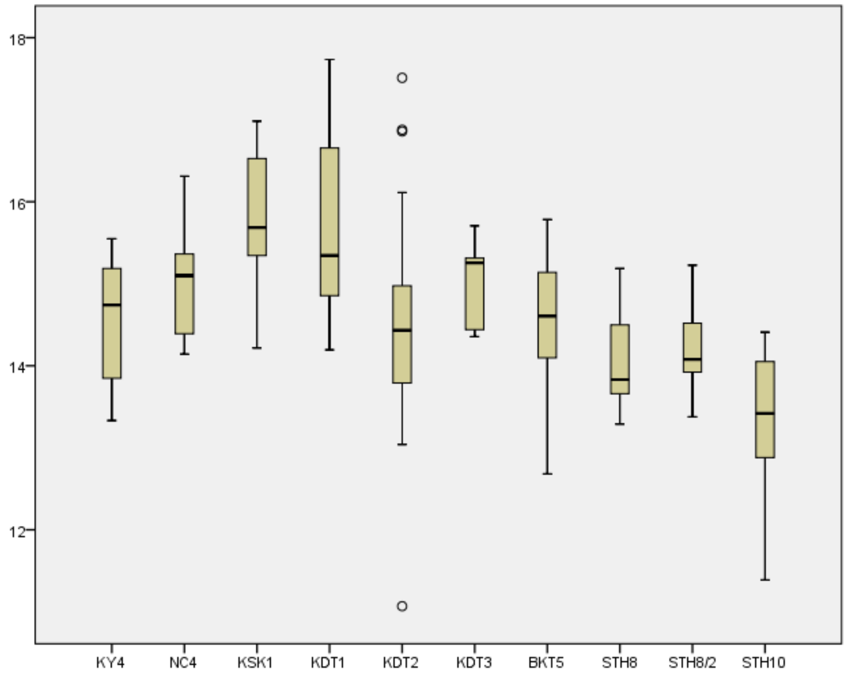


Figure 8.102 The boxplot shows the levels (wt%) of Al_2O_3 in the smelting slag across the studied sites

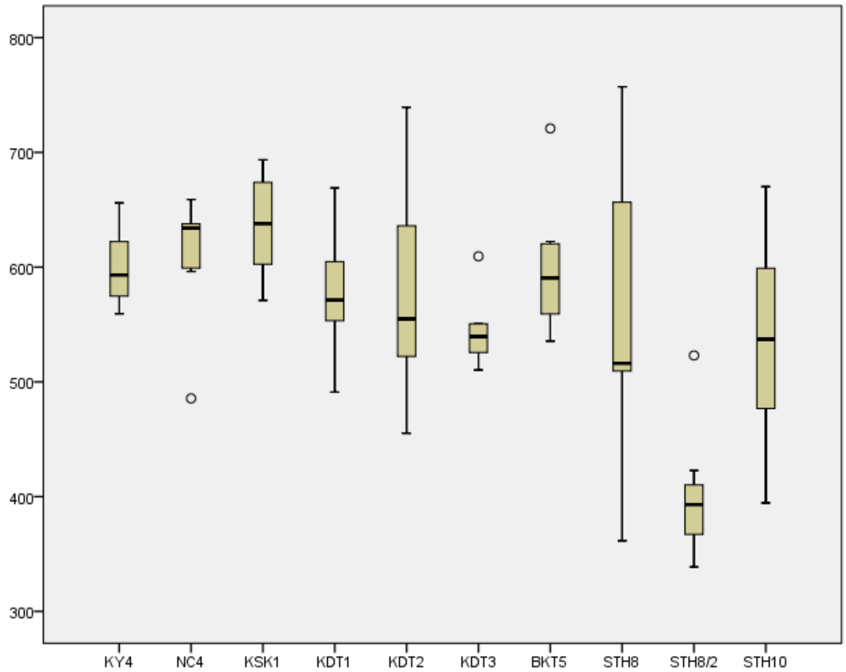


Figure 8.103 The boxplot shows the levels (wt%) of ZrO_2 in the smelting slag across the studied sites

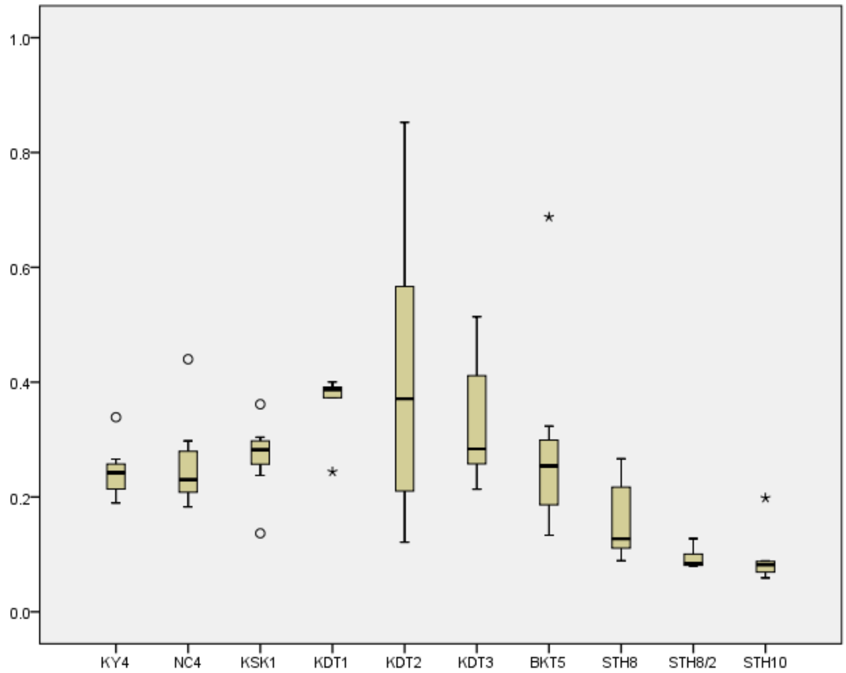


Figure 8.104 The boxplot shows the levels (wt%) of P_2O_5 in the smelting slag across the studied sites

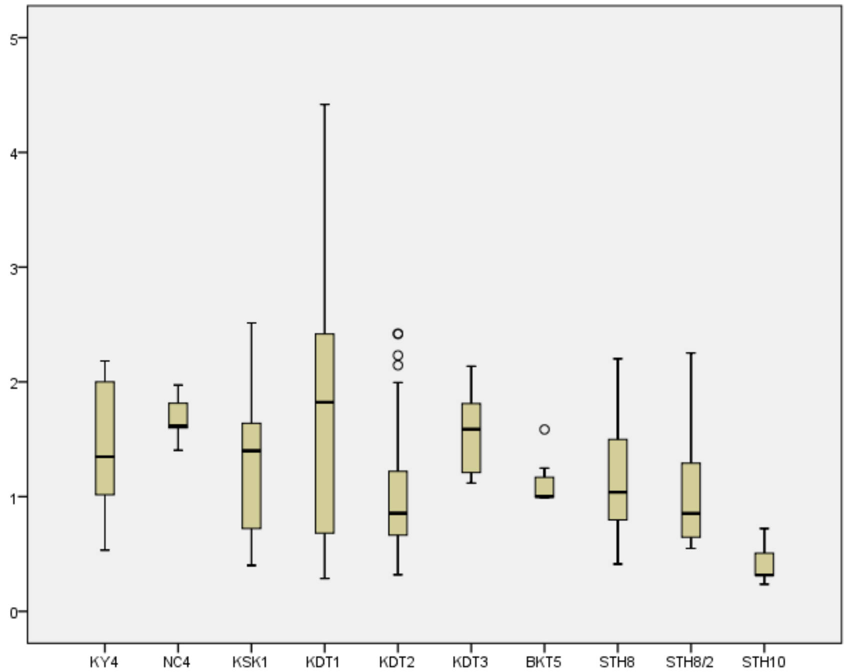


Figure 8.105 The boxplot shows the levels (wt%) of K_2O in the smelting slag across the studied sites

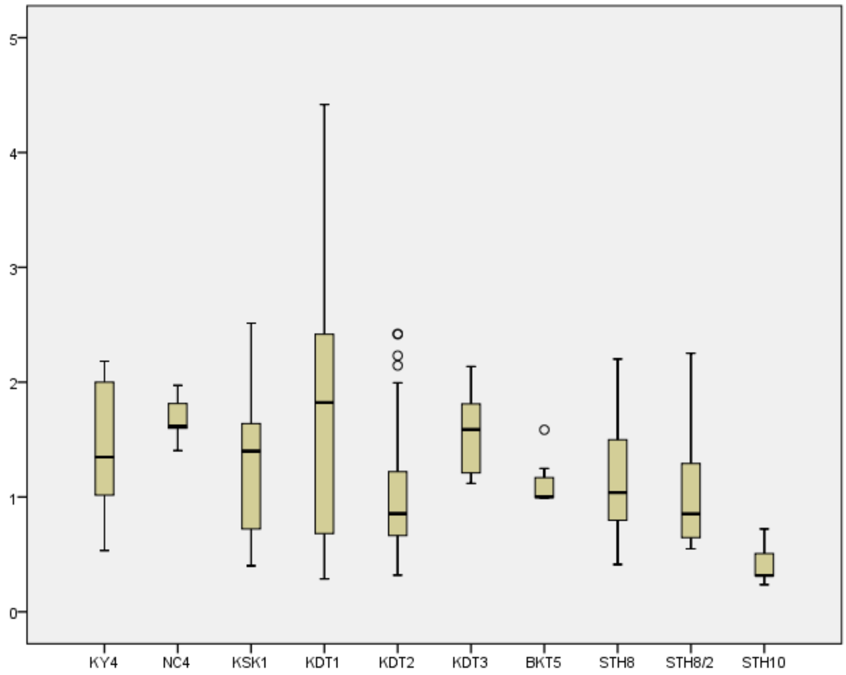


Figure 8.106 The boxplot shows the levels (wt%) of CaO in the smelting slag across the studied sites

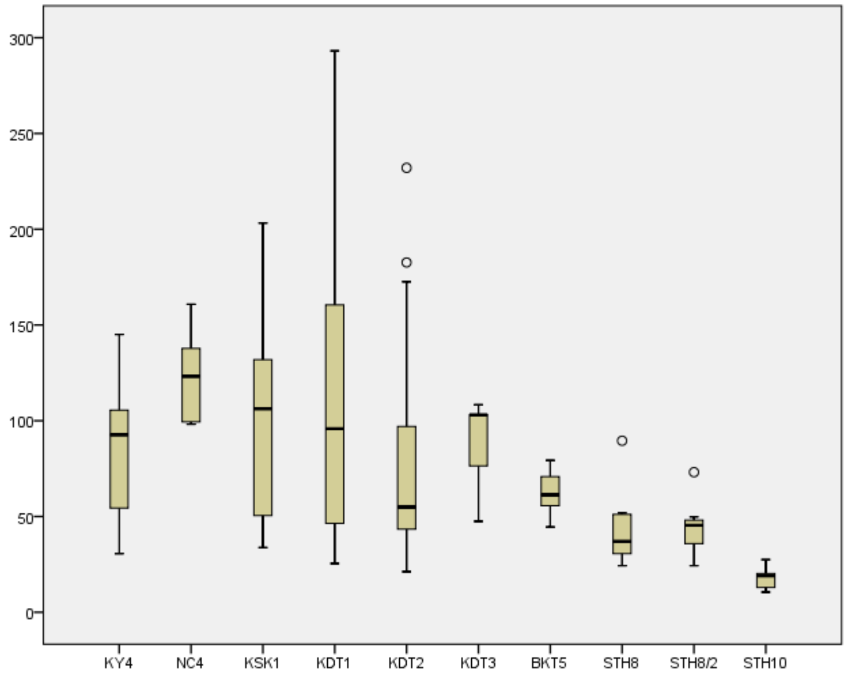


Figure 8.107 The boxplot shows the levels (wt%) of SrO in the smelting slag across the studied sites

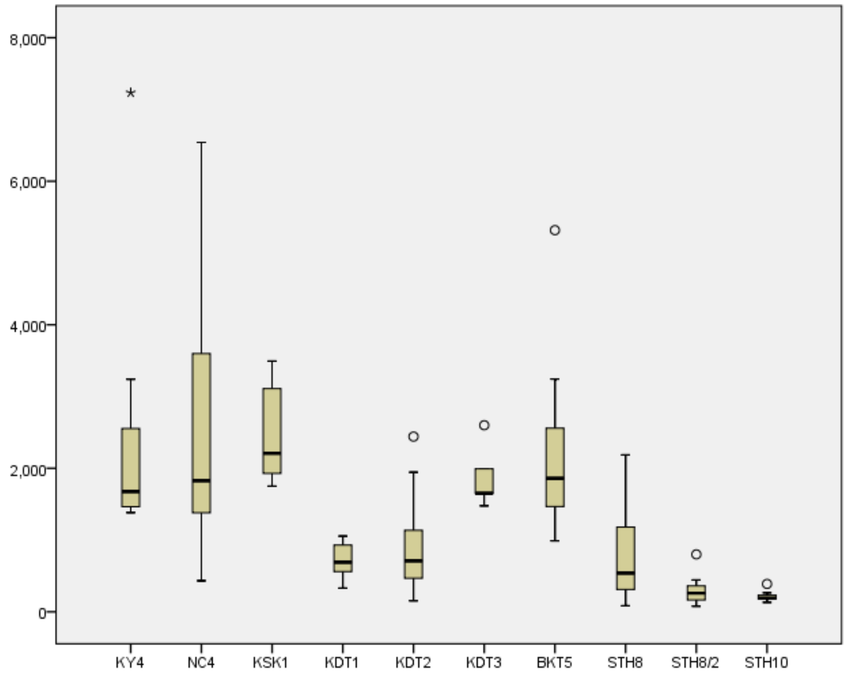


Figure 8.108 The boxplot shows the levels (wt%) of BaO in the smelting slag across the studied sites

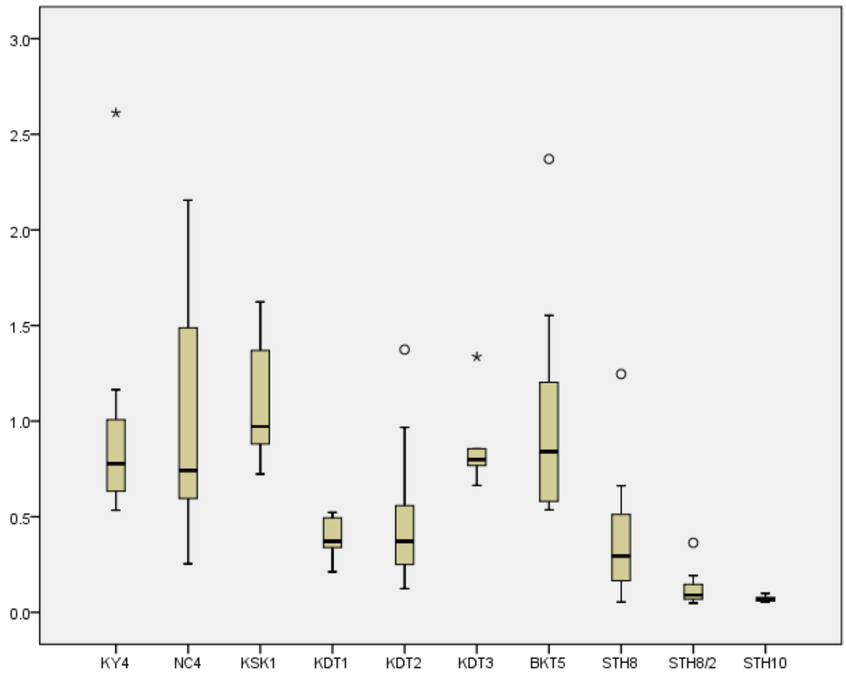


Figure 8.109 The boxplot shows the levels (wt%) of MnO in the smelting slag across the studied sites

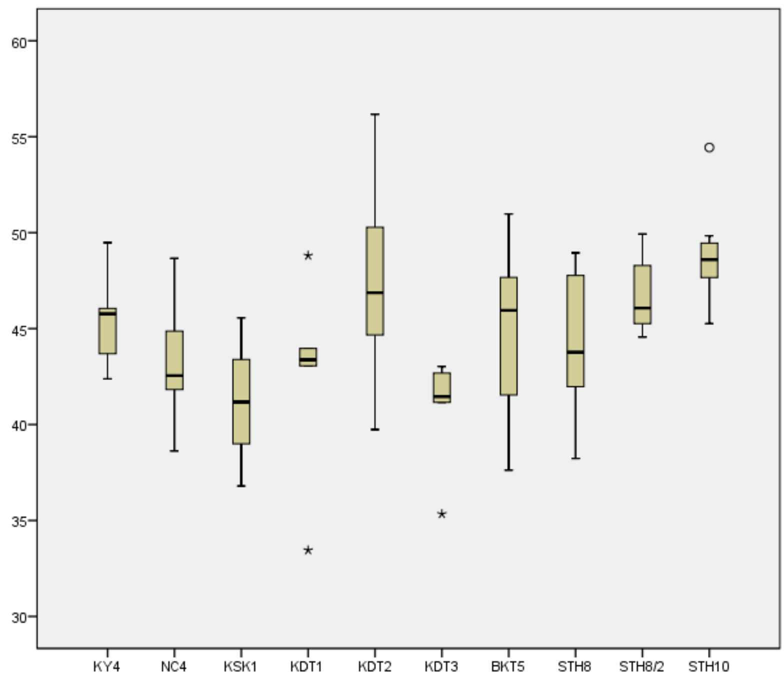


Figure 8.110 The boxplot shows the levels (wt%) of FeO in the smelting slag across the studied sites

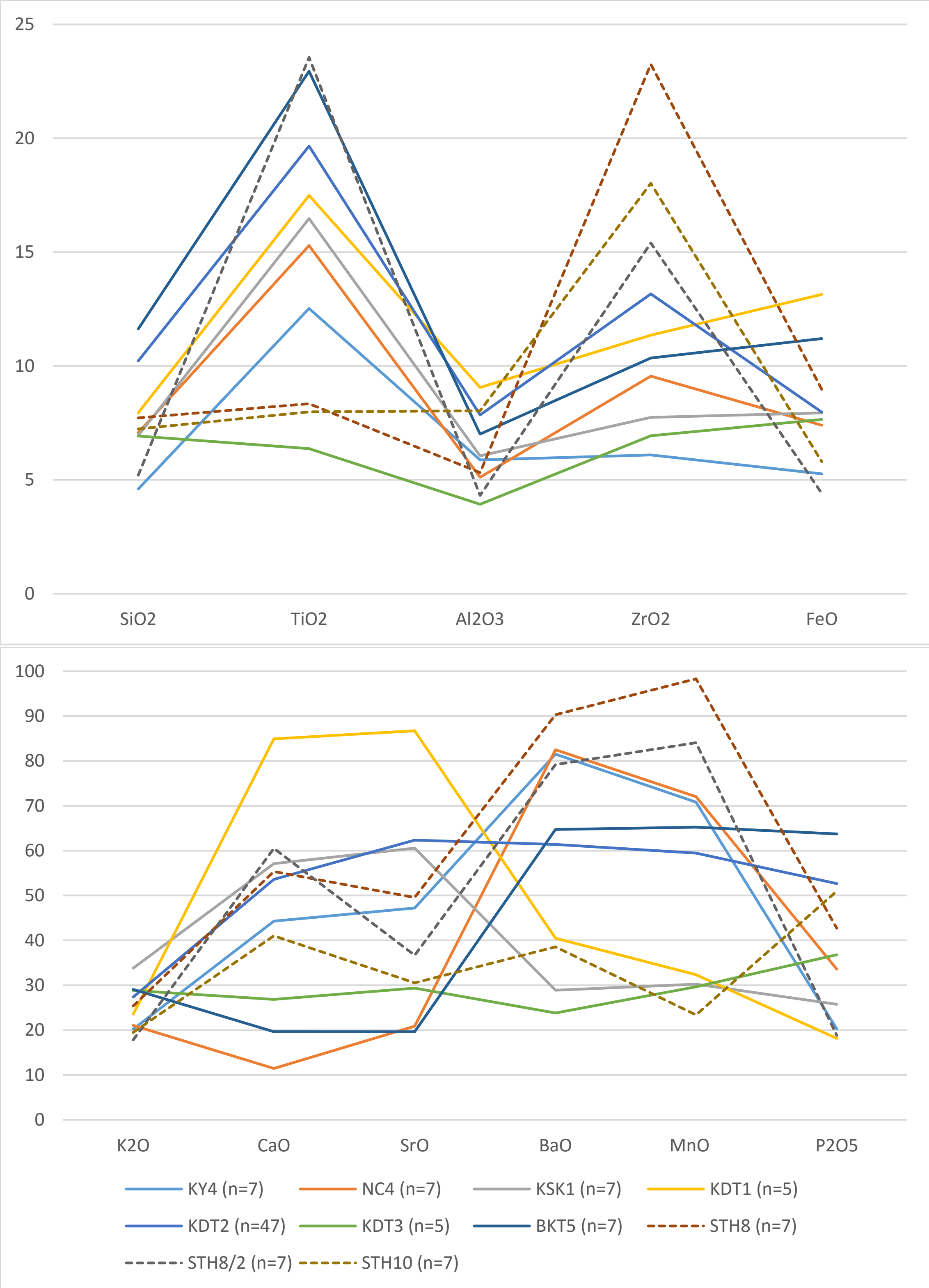
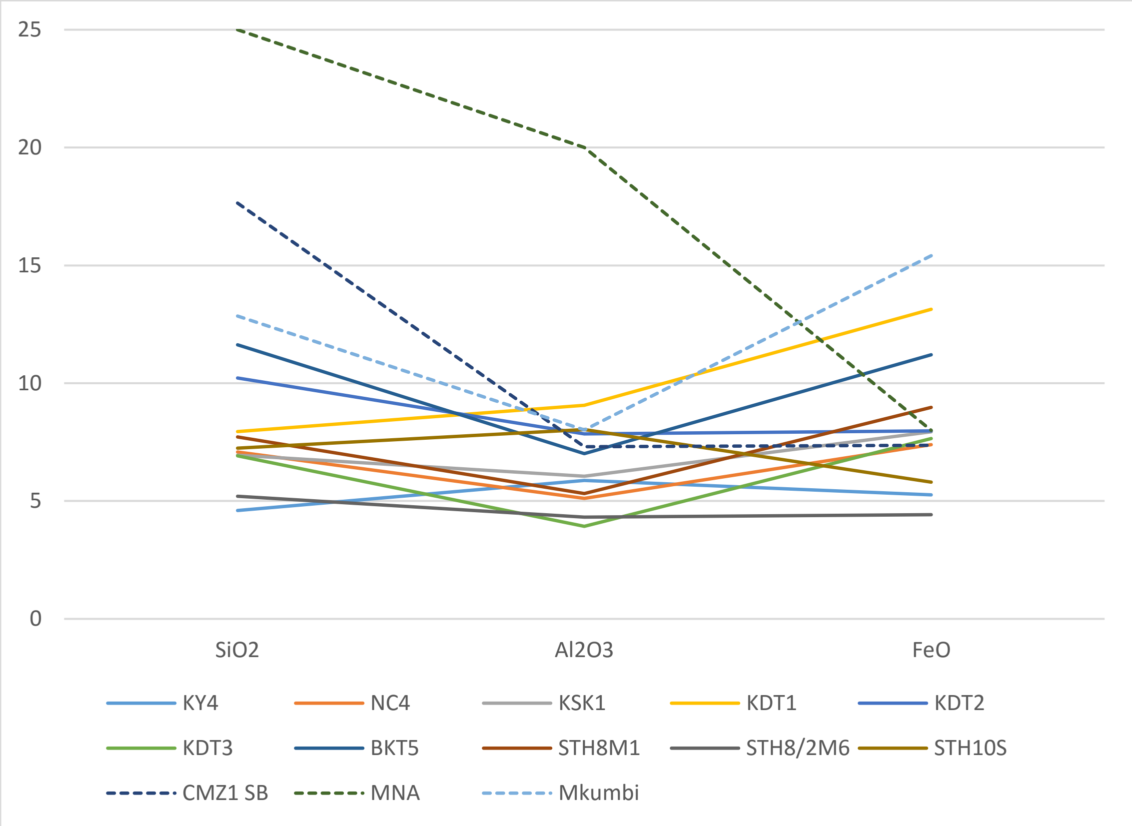


Figure 8.111 CV for selected key oxides in the sampled slag from all studied sites – calculated from average WD-XRF data, normalised to 100%. Solid lines represent the western group, whereas dashed lines mark the eastern group.



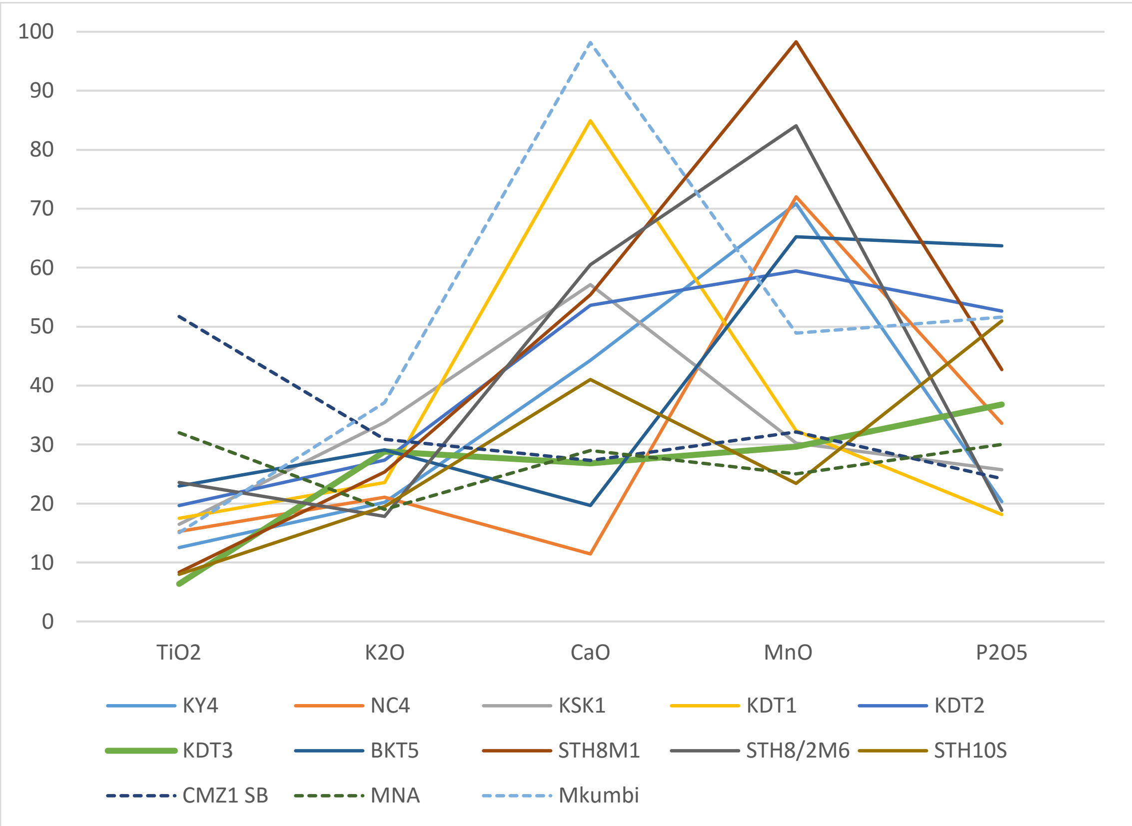


Figure 8.112 CVs for selected key oxides in the sampled slag from all studied sites (solid lines) compared to other laterite-related smelting sites from Africa: CMZ1 SB (Humphris 2010, 183), MNA (Humphris 2010, 284), and Mkumbi (Lyaya 2013, 181) (dashed lines) It should be noted that TiO_2 are considerably more variable in CMZ1 SB and MNA, perhaps due to the low precision of the XRF used for the analysis.

8.4.2.2 Groups and variability within a single site (KDT2)

As shown above, no significant between-site differences could be revealed across the Ban Kruat ironmaking landscape. KDT2, the only excavated site with stratified slag material available, allows a higher resolution approach, one that considers diachronic change. During the excavation, episodes of smelting activities were recognised (see section 7.2.4.1), and this allowed this study to track any changes in smelting practices by evaluating slag selected from each episode (Episode 1-7), probably covering a span of some 50 years of operation during the Iron Age (see section 7.3.1.1).

The multivariate analysis interestingly revealed that there may have been a diachronic change. This is seen in Figure 8.113 where slag from earlier episodes (EP5-7 – lower excavation levels) clusters in the right corner, whereas the samples from EP1-4 show a reverse, falling in the left side of the graph. Earlier slag tends to be richer in Al_2O_3 and SiO_2 along with ZrO_2, while the pattern of the slag in later phases is overall poorer in these oxides and richer in FeO and P_2O_5. This is also supported by RII values (Figure 8.114) which illustrates that slag seems to shift from being iron lean (EP4-7) to iron rich (EP1-3). This is likely to indicate a change in smelting parameters. One possibility is that less reducing atmospheres may have been desired by later smelters, perhaps to avoid the undesirable formation of cast iron. In terms of the ore smelted, laterite seems to have been smelted in each episode as indicated by no significant change in the *F*-Value (Figure 8.114); however, the chemical variability of MnO, BaO, and TiO_2 again suggests that different ore deposits may have been exploited (Figure 8.115). Although there is a shift of technology which was not revealed during earlier assessment of various slag sites, CVs show comparable levels of standardisation within each of the episodes (Figure 8.115).

This indication of technological shift is very intriguing since it was not revealed during earlier assessment of various slag sites. This may be due to small sample sizes and lack of controlled chronology. To determine if the same pattern could be revealed for other slag sites clearly requires more work. However, considering the range of sites and dates likely represented in the samples, this study can still assert that local ironmaking traditions remained largely comparable over time which involved the use of laterite and very high reducing atmospheres; although, there was a change in smelting behaviours but was still based on the same principle. The social implications of this conclusion will be discussed in detail in the next chapter.

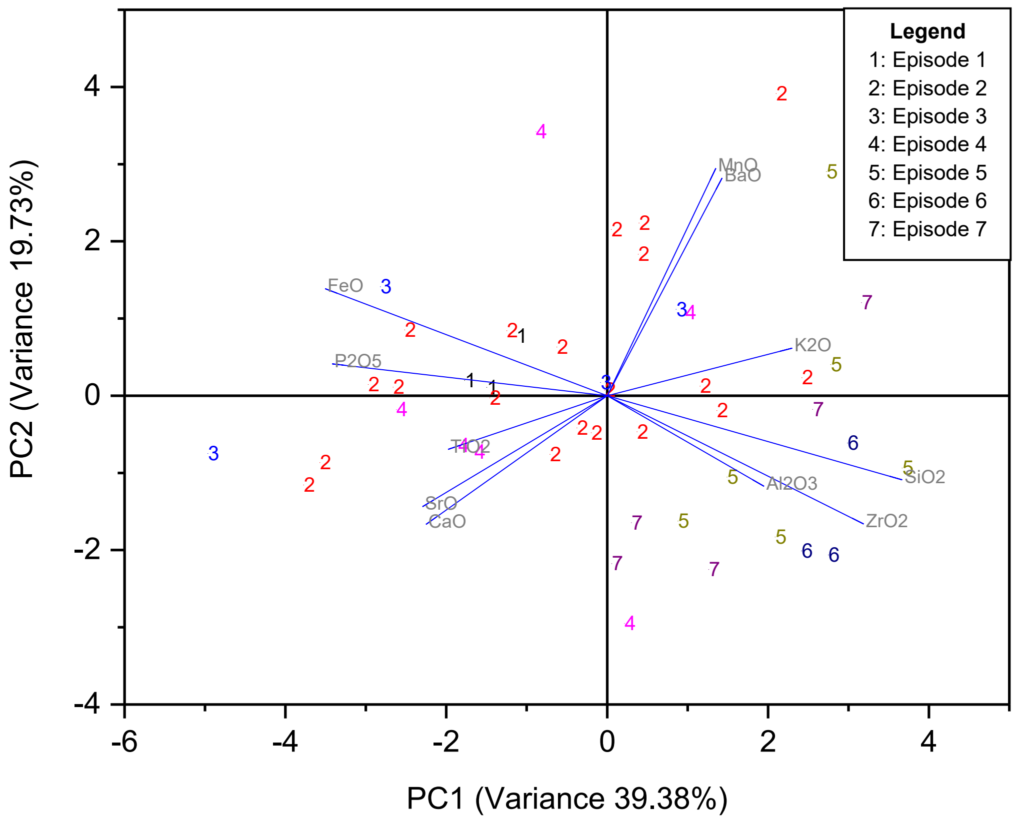


Figure 8.113 PCA plot for smelting slag chemistries from KDT2 (PC1 VS PC2) (first three components explain 72.90% of cumulative variance) (above).

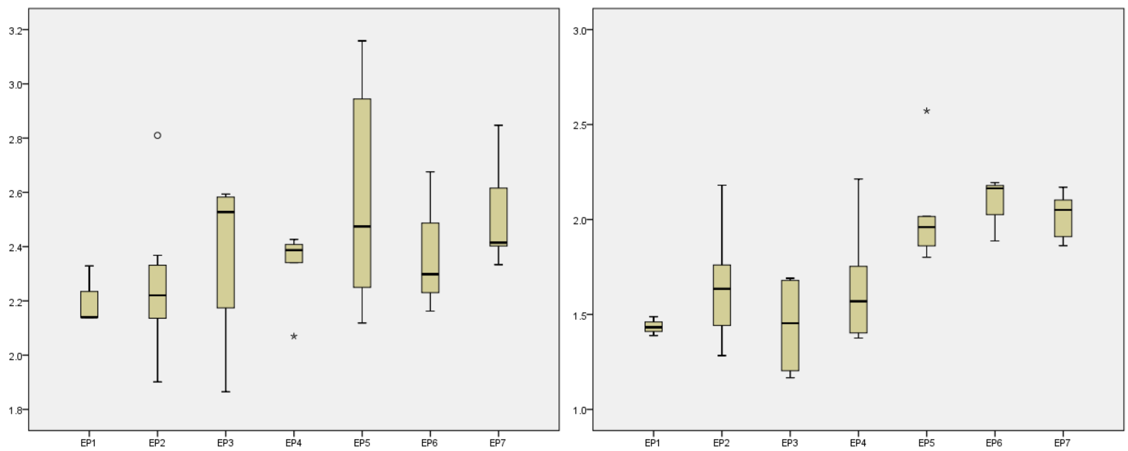


Figure 8.114 *F*-Value (left) and RII boxplot (right) of the values calculated from the WD-XRF chemical composition of the KDT2 smelting slag.

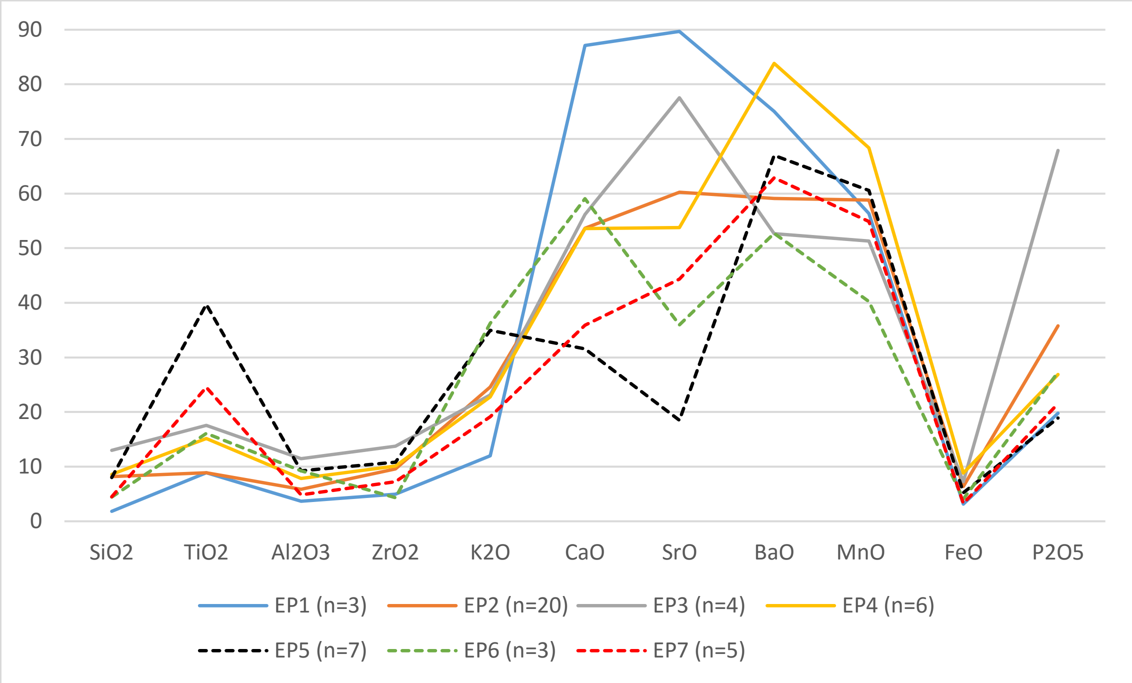


Figure 8.115 CVs for all key oxides in the sampled smelting slag from KDT2 – calculated from average WD-XRF data, normalised to 100%. Legend: EP1-7 represents smelting episodes documented. Earlier episodes – dashed lines. Later episodes – solid lines.

8.4.3 Iron smithing at KDT2 and STH8

The existence of the post-smelting activities was confirmed by the identification of convex smithing slag collections. A remaining question is what step of the smithing process this slag may represent, bearing in mind that the distinction between primary (bloomsmithing) and secondary smithing slag (forging/reparing objects) can be difficult (Serneels and Perret 2003; Veldhuijzen 2005, 185). Considering all evidence, it is possible that both kinds of smithing were present at these sites. At KDT2, only seven cakes of this slag were found, and these were directly associated with a smelting context. They are quite considerably different in size and shape among them. This suggests that they are a by-product from the primary smithing that may have taken place as soon as the bloom was retrieved from the furnace for initial consolidation. In contrast, the slag from STH8 T1 may represent a secondary smithing stage. Large quantities of this type of slag were found in the context associated with the hearth, iron artefacts, and, more importantly, outside the smelting zone. Moreover, the slag here often shows a fairly consistent range in size and shape, probably demonstrating that it was produced from a better controlled process. This may indicate that consolidated bloom produced at the nearby smelting mounds were sent to be transformed into bars or finished objects at this location of the site. Nonetheless, it is difficult to extrapolate this model to all of the sites without further excavated evidence.

Chapter 9 Social contextualisation of Ban Kruat iron production technology

9.1 Introduction

In Chapter 2, it was argued that comprehending a *chaîne opératoire* requires a consideration of both technical and social aspects. This is founded on the basis that ironmaking technology and organisation of production are shaped by the physicochemical parameters of the material as well as the environmental, political, and socioeconomic settings of society within which production takes place.

Chapters 7-8 discussed extensively the technical parameters of Ban Kruat ironmaking technology. In this chapter, these data will be integrated into associated environmental, political, and socioeconomic settings in order to explore the impact of social constraints on production (see Chapters 3-4 and 6). The previous model for the production sequence at KDT2 (see section 7.2.4.1) will be revisited in light of reinterpreted and new archaeological and archaeometallurgical data. This is hoped to build a more thorough picture of the technology in terms of its materials, techniques, and social dimensions.

Another issue to be explored further is how Ban Kruat ironmaking technology compares to other relevant cases. This comparison seeks to clarify how new findings improve our understanding of reduction mechanisms for laterite smelting and if there is any technical variation in currently known iron production in mainland Southeast Asia, particularly Thailand and Cambodia.

This reconstruction of the production process and identification of associated factors will facilitate further discussion on the organisation of iron production and its role and place in society. A social contextualisation of Ban Kruat iron production is hoped to be performed on two important periods: the Iron Age (5th century BC-5th century AD) and Angkorian Khmer period (9th-14th century AD). It should be remembered, however, that the current chronology for Ban Kruat metallurgical evidence only permits a reliable discussion for the Iron Age period (see section 7.3.1), while any discussion for the later period will necessarily be speculative. Concerning the transition period from late Prehistory to the Angkorian period (5th-9th century AD), related evidence has yet been found in Ban Kruat, but it is likely that the occupation as well as iron production may have been continued from late Iron Age to this period, as suggested by one charcoal sample from STH8. However, since evidence is very vague, a discussion on this particular period is left for the future works.

9.2 Ban Kruat ironmaking technology and its place in a wider technological context with emphasis on mainland Southeast Asia

9.2.1 Reconstructing the *chaîne opératoire*

For the sake of clarity, the discussion will begin with the main ingredients for bloomery production (e.g. ore, fuel, technical ceramics, and air supply) followed by furnace structure and operation and post-smelting activity, thereby tackling each operational step of iron production (i.e. from ore acquisition to forging of iron objects). This will summarise the technical findings presented in Chapters 7 and 8, while adding a number of additional relevant issues.

Ore

Archaeological and archaeometallurgical analyses indicate beyond question the use of laterite as an ore and how this was smelted to obtain iron in the Ban Kruat context (see section 7.3.2.3, 8.3.1, and 8.4.1.2). Two types of laterite: nodules (STH8) and cemented pisoliths (KDT2) ores were possibly exploited and smelted. Despite their different macrostructural appearances, their analysis characterised the ore samples as chemically indistinguishable in their heterogeneity. Whilst all samples are rich in alumina (8-14 wt%), other oxides, such as FeO, SiO_2, MnO, and TiO_2, vary depending on their source ore body. Importantly, iron oxide levels in the ore can range from 33-75 wt%, but is still overall poorer than typical iron ores (see section 8.3.1.1).

Laterite ores would have been locally available from deposits in and around Ban Kruat (at least within 0.1-10km from each cluster) (see section 6.2). There were at least two ore bodies; titania-rich, located on the western side of the research area, and titania-poor, located on the eastern side. MnO-containing laterite ores are also likely to have been exploited too as suggested by the mass balance calculations; although, potential local ore sources has yet been identified. Each ore body was very likely exploited by nearby workshops, as indicated by the slag chemistry (see sections 8.4.1.2.1 and 8.4.2.1).

To ensure a successful smelt, relatively FeO-rich laterite was specifically and necessarily selected (see section 8.4.1.2.3); however, there is no secure evidence for the method of ore extraction. Geologically, nodules are interspersed in layers of lateritic soil, and they can perhaps be sorted by digging through these layers (cf. Hillman and Hillman 2010, 118). Crushing solid laterite outcrop, which is already exposed to the ground level, into smaller chunks and then selecting FeO-rich pieces may also be plausible. To recognise suitable ores, density would have been an invaluable indicator of quality. The laterite ore was very likely not beneficiated mechanically very thoroughly as the material's friability would have resulted in an excessively small grain size poorly conducive to gas flow in the furnace (see section 8.3.1.2).

The use of this ore by Ban Kruat smelters may have largely been constrained by the geology of lower Northeast Thailand, where is almost devoid of typical iron ores (see section 3.2 and 6.2). According to modern geological surveys, small deposits of e.g. magnetite are only available along the border between Central and Northeast Thailand. FeO-containing laterite appears to have provided a much more widely available alternative resource for iron ore for local smelters, even if they still had to select the more iron-rich laterite. This implies that local smelters may not have had a problem producing iron from local laterite deposits as long as they were of the minimum quality needed for successful slag formation and the required technology and skills were possessed. Local smelters may have also benefitted from its self-fluxing nature, which would have facilitated smelting operations (see section 8.4.1.2.3). Nonetheless, this ore also came with big disadvantages to be overcome to successfully produce metallic iron. One solution involved the running the furnace hotter and more reducing, probably resulting in greater charcoal consumption than the smelting of typical FeO-rich ores. This condition will be visited again in the section concerning smelting operation (see section 8.4.1.4).

Fuel

Theoretically, charcoal supply is considered one of the key factors in iron production and demanded far larger volumes than ores (i.e. fuel:ore ratio for bloomery iron production ranges from 2:1 to as high as 19:1 (Cowgill 2003, 54; Gordon and Killick 1993)). Competing with other wood-based industries such as pottery making and land/forest clearance for agriculture would put more pressure on local woodlands (Gale 2003). Overconsumption of wood is thought to have led operations to terminate (e.g. Henderson 2013, 229-231; Schmidt et al. 1999, 240). Managing woodland should be seen as a key solution to sustainable charcoal supply for iron production (Gale 2003; Iles forthcoming; Paradis-Grenouillet *et al.* 2015).

At the moment, the data are too fragmentary to allow proper assessment of these issues, but some speculation can still be attempted. Although charcoal was certainly used as fuel (see section 8.3.3.1.1.1), no secure information has so far been available for the species of trees exploited in Ban Kruat. Moreover, it is also not clear if the same species of woods used for making charcoal as suggested by the ethnographic account of Ban Di Lung smelting were also exploited in Ban Kruat (see section 4.3.3). Further botanical identification of charcoal recovered from the excavations at KDT2 and STH8 will identify which species of woods were procured for this task.

Based on the technology employed for Ban Kruat laterite smelting, a considerable amount of charcoal was used to maintain the required temperatures and reducing atmospheres. Although the current data do not allow us to estimate how much charcoal was needed to produce iron using the Ban Kruat smelting tradition, and it is unclear how many workshops were operating at a given point of time, the operation may have put constant pressure on local woodlands. Other local activities, particularly the clearance of woodlands for agriculture and the archaeologically-attested pottery production would cause more stress to the local environment. The rapid deterioration of local environment, especially woodlands, may have occurred in the Angkorian period, when larger settlements, more intensified agriculture, and industrial-scale production of Khmer ceramics in addition to already existing iron production were established in the area. However, long occupation in the area and continuation of charcoal-based production activities may imply that local woodlands could have endured and been able to sustain demand from different social sectors. To better understand the relationship between high temperature industries and local woodland, a palaeoenvironmental assessment would be necessary.

Technical ceramics and clay

Three types of technical ceramics were associated with iron production: tuyères (nozzles and probable cylindrical tubes), clay plugs, and furnace fragments (see section 7.3.2.2). They were all produced using the same clay recipe, which was relatively alumina-rich clay heavily tempered with quartz (see section 8.3.2). This made these objects fairly refractory, able to survive high temperatures without failing but, at the same time, quite friable due to a loose internal structure (see section 7.3.2.2 and 8.3.2). The sources of clay cannot be identified but may have been local river bank deposits (see section 8.3.2.1). The materials were probably hand-formed. Their inconsistency in sizes, while retaining their overall shapes according to the type (i.e. clay plugs were generally in a water-drop shape), suggests that there was no control over the sizes and shapes of the materials (see section 7.3.2.2). It is plausible that their performance may have mattered more than standardised shapes and sizes.

What is interesting about Ban Kruat technical ceramics lies in their characteristic shapes, which are exclusive to Ban Kruat. Tuyère nozzles are considerably larger in overall dimensions (e.g. bore diameter, thickness, height, width, and length) than those found at other sites (cf. Pryce *et al*. 2014; Suchitta 1983, 193-194) (see section 7.3.2.2). Large bore diameter (3.6-4.5cm) probably facilitated stronger air injection into furnace, stimulating higher temperature. However, this wide bore also required an effective apparatus to produce a massive blast. Piston bellows or foot-operated bough-sprung bellows are suggested to have been used in the Ban Kruat context (see a discussion for a possible air-supplying apparatus used in the following section), it is unclear if they could have produced sufficient air blast required to create needed furnace condition. It is possible that this could have been achieved by introducing more bellows and tuyères per furnace, thus requiring more manpower to operate them. To address this issue regarding air supply, this requires experimental study. Technically sophisticated hydraulics may have been another possibility, but there is no evidence to support this proposal. It should also be noted that all slag sites are located at least 100-150m away from nearby stream.

Clay plugs, whose function was previously questioned, may be explained by the new findings. Its use was possibly related to a forehearth part (front part) (see Figure 7.27) which could have been used to manually remove slag out of the furnace, rather than slag tapping. Clay plugs were possibly used to block this hole in order to better seal the furnace promoting stronger reducing conditions.

Air supplying method

As discussed in section 7.2.4.1, no evidence for an air supply mechanism has been found. A wind-powered operation at Ban Kruat is unlikely (cf. Juleff 2009), but ethnohistoric accounts, either piston bellows (Bronson and Charoenwongsa 1994; Suchitta 1983, 195; see section 4.3.3) or foot-operated bough-sprung bellows, offer archaeologically low visibility possibilities by which may have been supplied into the furnaces visa the extant tuyères (Pryce et al. 2014, 144).

Furnace structure

Information about the Ban Kruat furnace structure was reconstructed exclusively from the excavated evidence found at KDT2. With the new technical data, a few points of the previous reconstruction may be refined, while the bulk of detail remains the same.

The furnace is reconstructed as a probable forced-draft cylindrical shaft furnace with a pear-shaped plan (see section 7.2.4.1). The same clay recipe was used for the construction. The structure is divided into two main parts: a forehearth/front part and furnace proper (Figure 7.27). The latter was a possibly circular chamber with a diameter of 60-80cm (possibly external diameter); this was where the charge was loaded. There is a possibility of different sizes of furnace (larger) used, as suggested by a slag block from STH8/2 M4 (150cm long and 110cm wide) (see section 8.3.3.1.2).

The technical analysis of the smelting slag suggests that the furnace had neither slag-tapping hole nor slag pit, revising the previous proposal of the presence of slag-tapping hole (Yoopom 2010). Excess slag was likely raked out from the furnace through a hole between forehearth and furnace proper in order to keep the operation going and be more thermally efficient. Since the superstructure of the furnace did not survive, it is postulated that the bloom could have been removed by completely or partly dismantled the furnace. The number of tuyères per furnace is unclear.

Smelting operation

The smelting stage may have begun with initial firing or reheating to get the furnace ready, but there is no actual evidence to confirm this step. The charge, which was probably a mix of laterite ore and charcoal, was then inserted at intervals; no additional fluxing agents, such as lime or manganese-rich minerals, were used. An arguably strong blast of air from bellow(s) (see a discussion in the above section "technical ceramics and clay") was channelled into the furnace to raise the temperature to at least 1,300°C. The production of CO gas from partial fuel combustion, and the reaction of that gas with unburnt charcoal (Boudouard reaction), would generate a highly reducing atmosphere. Both temperature and redox environment are arguably higher and stronger than typical bloomery smelting. This condition was necessarily maintained throughout the smelt by high charcoal consumption and bellows labour input. This furnace operation, which is likely to have been constrained by the ore properties and chemistry, is considered a strict approach that allowed metallic iron to successfully be reduced from this ore and prevented the crystallisation of hercynite before the end of the smelt. The creation of a

FeO-poor slag is considered another key factor to win iron from the comparatively low-grade ore.

In terms of the mechanism of iron formation, the process can be described as a two-staged process, which is often described in the smelting of typical iron ores (Blomgren and Tholander 1987; Killick and Gordon 1989). The first stage concerned a reduction of iron minerals, mainly iron oxyhydroxide, to free iron oxide, which would start to react with quartz and alumina to form slag. This slag became molten at approximately 1,300°C (see section 8.4.1.1 for a discussion on slag liquidus temperature), and remaining iron oxides, minerals, gangue components would all be dissolved into this melt. The free iron oxide then precipitated from the slag, which progressively became more viscous, and was further reduced to metallic iron when contacting with the carbon or reducing gases in the system. The reduction efficiency (how much iron was removed from the ore) can be considered high as no excess free iron oxide remained in slag, and as also indicated by the RII (see section 8.4.1.3).

Metallic iron forming in this viscous system would have had difficulty coalescing with other iron particles to form a bloom. Excess carbon in the system seems to have played a major role by promoting the carburisation of the metal. This reduced the iron's liquidus temperature, and the iron particles would have been able to travel through the slag more easily than in the solid state. Moreover, local smelters may have enjoyed a benefit of this carbon-saturated system as some steel would have been produced, along with more common soft iron. This production of steel may not have been an intention of local smelters, but rather an indirect benefit gained from the technical adjustment of the furnace operation for smelting laterite. Although this smelting system offered many advantages, it came also with an inevitable risk of producing cast iron, which could not be forged without de-carburising (e.g. fining) – a technological process for which we have no evidence in the region.

It should be stressed that, for most studied sites, the operation was considerably comparable in terms of the control of furnace condition with exception of KDT2, which could have been influenced by the employment of similar furnace operations despite the heterogeneity of the laterite ores. This implies that some skills of metalworkers needed to be possessed and that laterite smelting in Ban Kruat was already established and fully understood. To what extent this standardised furnace operation could also mean that the iron production was "controlled" will be discussed later.

Comments on smelting activities

From the technological reconstruction (see also section 8.2), the operation of laterite smelting in Ban Kruat was presumably labour and time-intensive. Every stage of smelting operation arguably required a considerable amount of labour to accomplish the tasks. Labours and time were necessarily required to sorting specific ore from layers of laterite, prepare large amount of charcoal, and operate bellow(s) throughout the smelting session. The latter may have been the most labour-intensive in Ban Kruat smelting operation in order to constantly supply sufficient air blast to the furnaces.

A set of skills was likely required in order to achieve the operation. Besides a skill to select particular ore pieces from laterite body, metalworkers needed to understand the behaviour of the furnace to successfully reach and maintain the vital smelting condition.

Comments on smithing activities and the location and spatial organisation of workshops

The new findings confirm the earlier hypothesis of post-smelting activities in specific areas, as seen at KDT2 and STH8 (see section 7.3.2.4), though the bulk of the slag deposits are associated with smelting. Metalworkers in Ban Kruat chose a location that was immediately adjacent to resources of water (100-150m) and possibly clay, while laterite may have been available nearby (0.1-10km). At KDT2, the presence of plano-convex slag indicates that bloom-smithing took place together with smelting (see section 8.4.3). At STH8, a different pattern was seen. Instead of individual workshops distributed within a cluster without an explicit pattern, we see a ring of mounds surrounding the flat area in the centre. Interestingly, this site pattern has never been found elsewhere in Thailand and possibly Southeast Asia. The mounds were involved in the smelting activity, whereas the central area saw the smithing and possible habitation activity (see sections 6.3.1, 7.2.7.1, and 8.3.3.2.1). However, as opposed to KDT2, this smithing activity at STH8 was associated with the forging of objects, supported by a different kind of convex slag (see section 8.4.3). This perhaps allows ones to speculate a scene which iron billets were smithed from blooms at the mounds and sent to the central area to be processed further. To confirm this hypothesis, however, we would need more detailed knowledge of the chronological relationships between the various mounds.

9.2.2 Implications for reduction mechanisms in laterite iron smelting

The smelting of laterite ores has received less attention than of more common ores (e.g. haematite and magnetite). From a review of related laterite smelting studies, their results have consistently emphasised the chemical variability of this ore type, and, in light of this, different smelting approaches (e.g. selection of specific ore type, ore blending, and furnace operations) are likely to have been formulated in order to cope with this chemical inconsistency in different contexts (e.g. Gordon and Killick 1993; Humphris 2010; Ige and Rehren 2003; Iles 2011, 2014; Killick and Gordon 1989; Lyaya 2013; Photos 1987). To date Gordon's and Killick's (1993) ethnographic case study from Kasungu, Malawi provides the most comprehensive reconstruction of the reduction of iron from a laterite ore (see section 4.3.3.2). In addition, Kasungu and Ban Kruat appears to share a common feature in which laterite ore was the only source of iron available to local smelters (Gordon and Killick 1993, 259). The analytical work presented in this thesis is compared here with the findings from Kasungu in hope to bring another example that can be integrated into our growing understanding of iron production from non-standard ores. To facilitate a comparison between two productions, their reconstructed mechanisms are reiterated.

The Kasungu mechanism of iron formation involved in a direct reduction of iron oxide to metallic iron in the ore, which was very iron-poor (20-30% Fe) and mainly contained large quartz grains as gangue. The process was performed in the low-temperature and low-reducing zone of a natural-draft shaft furnace, consuming large quantities of charcoal (i.e. fuel:ore ratio was about 19:1). A key factor for this successful formation of iron lay in the selection of the ore with large quartz grains. The very high refractoriness of these grains meant that they remained largely intact during the smelt and thus the quartz of which they were comprised was effectively not part of the smelting system. This artificial reduction of the ore's bulk SiO_2 content meant that less FeO was needed for slag formation, leaving more FeO was available for reduction to iron metal. The low viscosity slag, probably suggesting that the system was not affected by alumina, then drained readily out of the formed iron. This iron agglomerated under influence of gravity into a bloom (see section 4.3.3 for a detailed discussion).

Compared to this model, the Ban Kruat process is fundamentally different. The laterite ore was relatively richer in FeO and alumina. Higher temperatures and more reducing atmospheres were employed in a forced-draft cylindrical shaft furnace. Although its fuel consumption cannot be calculated, a considerable quantity of charcoal, higher than typical bloomery smelting, was presumably consumed. As summarised in the section “smelting operation” above, this is a two-staged process, in which iron was formed from the free iron oxide precipitated from the slag melt, unlike that observed in the Kasungu mechanism.

The difference in smelting conditions employed for each instance appears to have largely been related to the ore chemistry. As proposed throughout Chapter 8, these conditions were performed as they were suitable and achievable for the ore available. However, the constraints behind their actions may have been different.

The practice of Kasungu smelting was inherently difficult to control due to the use of a low-grade ore and natural-draft furnace and to improve the productivity (Gordon and Killick 1993, 267). However, this tradition seemed suitable for the Kasungu society (Gordon and Killick 1993, 266-267). Technically, very iron-poor laterite was the only one available locally; therefore, such technology had to be formulated in response to this constraint. Socioeconomic factors were also seen influencing the technology and explaining why this “economically inefficient” technique was preserved. Firstly, male workers were required to work in the field, thus fewer workers could help bellowing. Moreover, sufficient supplies of charcoal might have already been made available during an agricultural cycle, thus there was less concern about consuming a lot of charcoal. Also, the smelting activity was not market-driven. Social beliefs (magic) perpetuated the idea that practice had to carry on (Gordon and Killick 1993, 267-270).

Similar parameters may be raised for explaining Ban Kruat smelting, even though their specifics are different. The type of ore used was likewise dictated by local geology; the ore available was considerably richer in FeO, but also in Al_2O_3. In light of the ore chemistry, it is posited that the Kasungu method could not have been employed by Ban Kruat smelters, and vice versa. If smelted using the Kasungu tradition, the Ban Kruat ore type, which was full of smaller quartz grains and alumina, would be unlikely to produce metallic iron as all the FeO would be bound with quartz and alumina in the slag. Similarly, if the Kasungu type of ore was to be smelted by using the Ban Kruat furnace operation, the result could not have produced metallic iron as its ore was too poor, and the slag, if created, would be too viscous for iron to travel. On this basis, the Ban Kruat ironmaking method was essentially dictated by the ore. Likewise the Kasungu smelting, charcoal consumption was presumably high; however, this high consumption was needed to maintain the desired smelting conditions mentioned above. To what extent socioeconomic factors may have influenced this technology will be evaluated in the section 9.4.

This thesis offer another example for the mechanism of iron formation in laterite smelting. In actuality, published research on "laterite" smelting seems to illustrate this two-stage process, judging by their slag microstructures which were relatively reacted; although some residuals still existed (Humphris 2010; Ige and Rehren 2003; Iles 2011; Lyaya 2012, 2013). However, it is possible that comparatively higher iron content in ores (above 55-60 wt%) may have been a key factor permitting smelters to operate this mechanism.

9.2.3 Ban Kruat iron production tradition in mainland Southeast Asian ferrous extractive technologies

As reviewed in Chapter 4, the study of ferrous metallurgical activities in this part of Southeast Asia is underdeveloped as compared to other parts of the world, such as Africa and Europe. A consequence is that there is no overall picture of this technology and no substantial regional data to argue for its development through time. Existing knowledge has been based on very limited examples, mainly from Thailand (Nitta 1991; Suchitta 1983). The situation has been improved recently by increasing number of studies (Biggs *et al*. 2013; Chuenpee *et al*. 2014; Mohktar 2012; Pryce *et al*. 2011; Pryce *et al*. 2014; Venunan 2011; Yoopom 2010). Regional variability of this technology has begun to come into sight.

This section aims to explore this technological variability, regardless of their chronology, in order to see if the laterite smelting technology at Ban Kruat could be considered a regional tradition of lower Northeast Thailand. Moreover, this is hoped to find its place of Ban Kruat iron production in the technological realm of mainland Southeast Asia. To facilitate this exploration, a FeO-SiO_2-Al_2O_3 diagram was employed, for these three dominant components were available in all datasets, while other oxides were not consistently reported. Considering limited sampling and differences in analytical methods, any interpretation here would have to be done with caution, and further systematic studies are needed to better our understanding.

Smelting slag seems to concentrate on the diagram broadly in two areas: near optimum 1 (Ban Kruat, Ban Kra Thom, Ban Khok Muang, Ban Ya Wuk, Ban Ta Nein, Ban Khe Lhek, and some of Ban Dong Phlong samples, all are in lower Northeast Thailand) (hereafter G1) and in fayalite region (the rest of the sites, including other lower Northeast Thai sites: Ban Si Suk, Ban Don Klua, and Ban Bung Kae – G2) (Figure 9.1). On a wider scale, these slag samples illustrate a regional variability, likely to be dictated by different ores and the subsequent furnace operations.

For the G2 sites, the difference from the G1 sites may be best explained by the use of typical iron ores. The proximity of typical iron ore deposits and the remains of these ores at some of the G2 sites, such as Sungai Batu (Mohktar 2012), Ban Di Lung (Suchitta 1983), and PD/PKKS (Pryce *et al*. 2014) support this observation. As expected from the smelting of these ores, their resultant slag is rich in FeO and low in alumina with the exception of Sungai Batu, where the ores smelted were relatively rich in alumina (5-8 wt%). Collectively high FeO content in all slag supplemented by the presence of wüstite in the slag from the three aforementioned sites indicate that the furnaces' atmospheres were less reducing.

The G1 group, made up by the sites in the same region as Ban Kruat, shows a more interesting pattern. The slag is largely sub-divided into two groups: alumina-rich (Ban Kruat and Ban Kra Thom – 12-14 wt%) and alumina-poor (the rest of the sites – 5-7 wt%) (Figure 9.2). Exceptionally, Ban Dong Phlong slag falls in between these two groups as it contains varyingly levels of alumina (9-11 wt%). As the site is likely to have smelted laterite, its high variability is possibly caused by different grades of laterite smelted or laterite and standard ores mixed and furnace operations employed. However, problems with analytical method (e.g. contamination from other materials in slag) cannot be ruled out.

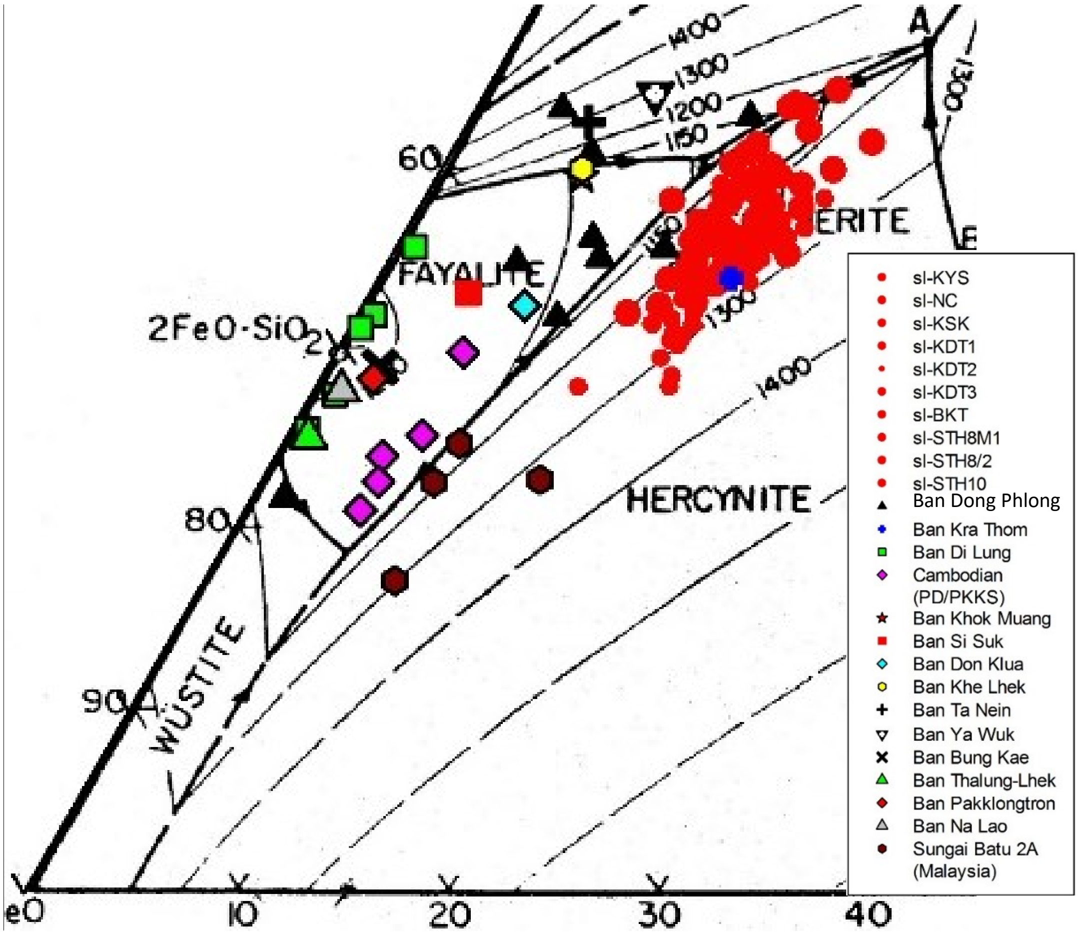


Figure 9.1 A comparison between Ban Kruat smelting slag (red circles) and some probable smelting sites in Thailand (Ban Dong Phlong (Nitta 1997), Ban Kra Thom (analysed by the author of this thesis), Ban Khok Muang to Ban Na Lao (Suchitta 1983)), Malaysia (Sungai Batu (Mohktar 2012)), and Cambodia (PD/PKKS (Pryce et al. 2014)) using the FeO(+MnO+CaO)-SiO_2-Al_2O_3(+TiO_2) ternary phase diagram. Each symbol in the diagram represents each sample.

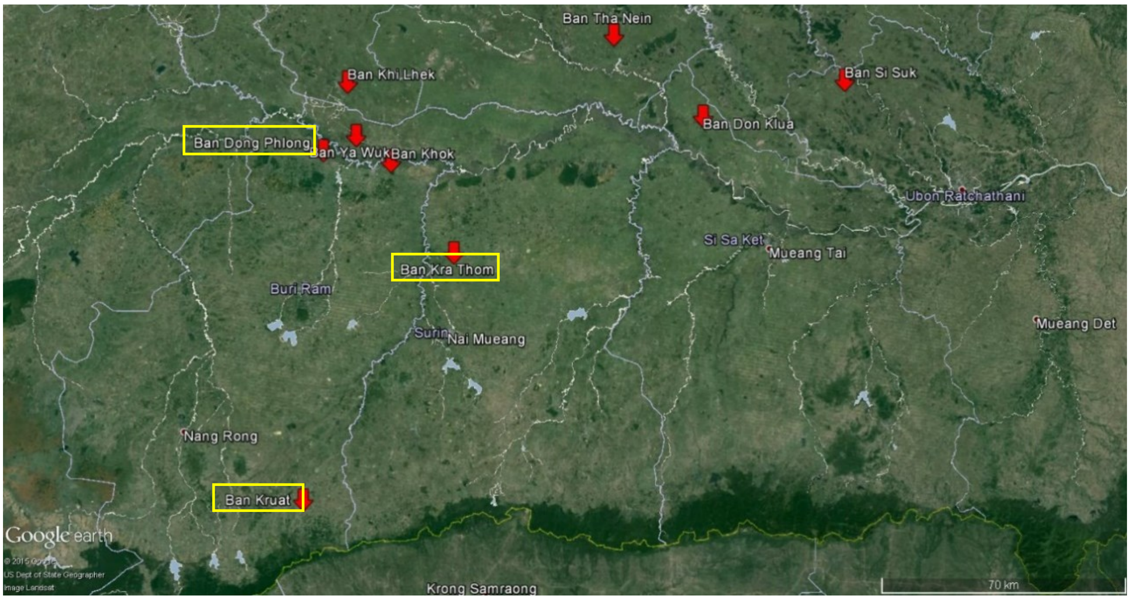


Figure 9.2 Locations of the iron slag sites in lower Northeast Thailand mentioned in the previous figure. The sites with yellow boxes are those associated with laterite smelting.

Nonetheless, the pattern observed again illustrates a variability in the ores smelted and furnace operations employed in this specific region. On the ores used, this can be interpreted in two ways. Firstly, there is a possibility of the existence of small typical iron ore deposits that have been overlooked by modern economic geologists. Secondly, if laterite was commonly smelted in lower northeast Thailand, which cannot be proved using the current data, its chemical variability (e.g. high-grade laterite containing high FeO and low Al_2O_3 was smelted) could explain these sub-groups. Some comments can be made for another possible laterite smelting site. A sample from Ban Kra Thom has the potential to be another example of laterite smelting. The macro- and microstructure as well as slag chemistry are very similar to Ban Kruat. However, to confirm this issue, a systematic characterisation of more samples is needed.

On this basis, the regional variability of slag chemistry in mainland Southeast Asia seems to have been largely constrained by the availability of iron ores in each geographical area. A related inference is that smelters mainly exploited nearby ore deposits. This variability further suggests that there were different sets of preferences and skills in smelting involved among regional smelters. Nonetheless, the most interesting observation applies to lower Northeast Thailand, as the above comparison has raised a possibility that iron smelting in this region may not have been solely reliant on laterite. Nevertheless, to obtain a better picture of regional use of laterite in iron smelting, more archaeological study of the potential sites and the creation of database of regional laterite and slag chemistry needs to be done. Without them, it is very challenging to confidently evaluate this hypothesis.

To conclude by stating the place of Ban Kruat iron technology in wider mainland Southeast Asia, Ban Kruat characteristics of smelting parameters (e.g. control of the furnace operations) and technical ceramics (e.g. very large tuyère nozzles and clay plugs) differ considerably from other known examples, probably excluding Ban Kra Thom.

9.2.4 Hypothesis on the origin of laterite smelting in Ban Kruat

The findings in the previous section show that the laterite smelting style in Ban Kruat represents a distinctive technology in lower Northeast Thailand. The consistency of the data further suggests that the technology and its practice remained unchanged and reasonably standardised from the earliest known smelting context at KDT2 (approximately AD200) (see section 7.3.1). This means its practice could be repeated and was able to control and limit technical errors involved; no indicators of an experimental stage at Ban Kruat have been identified (cf. Pryce 2008). Examining earlier practices of laterite smelting may help provide useful clues for this issue; however, the only confirmed example is known at Ban Dong Phlong (BDP), located approximately 100km north of Ban Kruat and dated to the 2nd century BC, c. 500 years earlier than the activity at Ban Kruat (Nitta 1991, 1997 and see sections 4.3.1.1 and 4.3.3.3). It has to be noted that, in light of very limited associated evidence, detailed discussion surrounding this issue is difficult and unavoidably speculative.

In terms of their archaeology, both sites have not, although located in lower Northeast Thailand (Figure 9.2), yielded any evidence for direct socio-cultural connection (i.e. they were in the different sub-cultural systems). However, regional archaeology allows us to posit that they might have been connected to some extent through the active interregional exchange networks known to have existed in the Iron Age (e.g. Bellina 2014, Carter 2015; Dussubieux and Gratuze, 2010; Pryce *et al.*, 2014). These active exchange networks could have acted as a medium allowing this laterite smelting knowledge to be passed from one smelting locale, like Ban Dong Phlong to other smelting locale, including Ban Kruat. However, on the basis of their iron smelting technologies, there is no strong correlation between them, apart from them both using laterite ores. A hypothesis could be made from the observation of chemical variability (CVs) (Eerkens 2000; Eerkens and Bettinger 2001) of smelting slag from both sites.

In early laterite smelting (c. 200BC), represented by BDP's high slag chemical variability (CVs are above 18% for three dominant oxides (SiO_2, Al_2O_3, and FeO)), the practice may have not been fully understood and unable to control the variability of laterite ores. This may be interpreted as an experimental stage (see Pryce 2008 for another example of an experimental stage in early metal production).

In the period between BDP and KDT2, there has been no contemporary evidence in lower Northeast Thailand, not only for laterite smelting but iron smelting in general. At some point during this period, Ban Kruat was occupied, evidenced in Ban Bueng Noi and STH8's lowest excavated level. Iron smelting started then at a small scale, and this knowledge was possibly brought into this upland zone by the settlers from the floodplains in lower Northeast Thailand (Moore 1988; Welch and McNeill 1991; see a discussion of an Iron Age expansion of communities to the uplands in section 3.2) or even from Northwest Cambodia in order to secure new lands and resources, including iron and other forest items. Nonetheless, considering the lack of typical iron ores (e.g. haematite and magnetite) in and around Ban Kruat landscape (the closet known typical iron ores is located 100km to the east of Ban Kruat), it is logical to deduce that laterite was exploited from the beginning. On this basis, two scenarios can be hypothesised. The first scenario posits that that early Ban Kruat smelters already knew this ore and how to smelt it, thus being able to extract iron out of this ore. The second scenario sees that there may have been an experimental stage as a result of early smelters, who were already experienced in smelting of standard ores, explored the new landscape looking for new ores to try; however, the remains may have been so few and have yet been recovered.

By the late Iron Age (c. AD200), the laterite smelting practice at KDT2 may have already been understood as stated earlier (evidenced in lower chemical variability, compared to BDP (see section 8.4.2)). Thus the local characteristic tradition took shape (e.g. unique sets of technical ceramics), as part of an adaptation to local laterite chemistry.

9.3 Social contextualisation of Ban Kruat iron production: organisation of production and contributions to local and regional archaeology

Before the choices and constraints behind the iron production in Ban Kruat can be concluded in the next section (9.4), it is necessary to first comprehend how Ban Kruat iron production was organised, and more generally to assess how this thesis contributes to our knowledge of the archaeology of Ban Kruat and lower Northeast Thailand. Hypothetical models for the organisation of production (see section 4.3.5) will be evaluated with the reconstructed *chaîne opératoire* and technological constraints discussed earlier.

9.3.1 Contextualising Ban Kruat iron production in the Iron Age context (5th century BC-5th century AD)

In Chapter 4, it argued that iron was needed for increasingly intensified agricultural production and large-scale landscape engineering related to water conservation. This suggested that iron production could be considered a socioeconomically essential production during this period. An expansion of the communities in the floodplains to occupy the uplands was proposed to have been related to a need to secure new resources, which laterite iron ore was one of them (Moore 1988; Welch and McNeill 1991). Nonetheless, evidence for iron production in lower Northeast Thailand seemed to be associated with forging/repairing of objects rather than smelting activity. Moreover, the latter evidence appeared to have been confined to only some able communities. As the production, at least the skill to conduct the extracting operation, was not commonly carried out by all settlements, this primary iron production was seen to have been specialised and may have provided an opportunity for local elites to generate wealth and power by controlling it (see section 4.3.5.1 for a discussion in length).

To evaluate this model, it is essential to clarify the organisational nature of iron production (non-specialised vs specialised) in light of Costin's discussion of organisation of craft production (1991, 2001; Costin and Hagstrum 1995). Clarifying this may allow us to better understand the socioeconomic and political organisation of lower Northeast Thai and Ban Kruat Iron Age societies. This is also to evaluate if iron production could be perceived as an elite political strategy, allowing them to compete with others during a period when some Southeast Asian social groups became increasingly complex and hierarchical (Higham 2011b, 2012, 2014, 2015).

However, pursuing an assessment of Costin's models based on the current fragmentary nature of the data inevitably faced difficulty. Some issues, such as the spatial relationship between producers and consumers, scale of production (number of workshops operating at one time), input and output of the production, and social status of producers could not be dealt with convincingly. Still, the organisation of Ban Kruat iron production can be characterised by some culturally-contingent attributes, such as standardisation, costs and benefits of the production, and skills, which are available from this present study

(Costin 2001, 2005; Costin and Hagstrum 1995; Li *et al*. 2014; Martinón-Torres *et al*. 2014; Pryce *et al*. 2010; Pryce *et al*. 2014).

The first measure to be assessed is standardisation. The compositional conformity, resulting in relatively low CVs (see section 8.4.2), can be interpreted as indicating high technological standardisation. As proposed, ore constraints are likely to have forced local smelting behaviour to be consistent. This possibly corresponds to what Costin called "intentional" standardisation, which is related to technological properties of the production (Costin 2001, 302; Costin and Hagstrum 1995, 622). Ban Kruat metalworkers were controlling the smelting quite tightly in response to a relatively difficult to smelt ore. Although Ban Kruat's standardisation may not be a good indicator for organisation of production as it was intended to meet a specific technical requirement (Costin and Hagstrum 1995, 662), this standardised smelting behaviour among different workshops may at least be suggestive of the existence of specialists working on site. The smelting was practised frequently, probably demonstrated by 4m of slag layers at KDT2, and became more routinised which created fixed gestures (Leroi-Gourhan 1993) and processes. The production then became conservative and able to minimise risk by consistently selecting similar grades of ore, as seen in the layers of production activity at KDT2 (see section 8.4.2.2; Figure 7.25). In light of this established practice, it suggests that not every member of community could have participated in smelting activity but only some members who were trained to become capable metalworkers (e.g. able to recognise suitable ore nodules and supervise low skilled labourers). This may suggest that Ban Kruat iron production was a specialised production. Other workshops in Ban Kruat, despite lacking a good chronology, saw the same specialised well controlled production (see section 8.4.2.1). It would be risky to attempt to use this arguably "intentional" standardisation as a proxy for the relative number of smelters involved in the activity (cf. Costin 2001, 302; Costin and Hagstrum 1995, 622) or intensity (scale) of production based on coefficient of variation (cf. Roux 2003, 780).

Costs of production in the Ban Kruat context can also be speculatively interpreted from the technical data. They are referred to here in terms of energy, time, labour, and raw material input to the work (Costin 2001, 2005, 1067). As discussed above (see section 9.2.1), the smelting operation in Ban Kruat is considered to have been labour and time-intensive for the process needed the investment of these resources in order to ensure the successful outcome.

Whilst Ban Kruat iron production was not 'economically efficient' as compared to some other processes, it was able to answer to local demand of iron when the alternative would have been to import it via potentially unstable supply networks.

Overall, great investment of skill and resources (labour and time) was made primarily for this specialised Ban Kruat laterite smelting. This is likely to emphasise an importance of iron in Ban Kruat Iron Age society. Iron was necessarily needed in this area for increasingly intensified agriculture, land clearance, and probably increasing conflicts between elites (see Higham 2014 and sections 3.2, 3.3.2, and 4.3.1). It may be possible to speculate that iron produced in Ban Kruat may have also been exchanged with other non-iron-producing settlements for other items, but this requires a study on the distribution of iron in lower Northeast Thailand to test this hypothesis.

The above interpretation is then used to explore the intensity of the production, which concerns the degree of involvement of specialists in the production (full-time or part-time) and thus the degree to which the producer is free from their own subsistence activities and dependent upon others (attached or independent producer) (Costin 1991, 5, 2001, 279-280; Wailes 1996). An attempt will be made to characterise the production in terms of Costin's types (1991, 8-9). These types of specialised production (e.g. individual specialisation, dispersed workshop, and community specialisation) are known to be largely governed by social setting of society (Costin and Hagstrum 1995, 621). Again the result is by necessity speculative due to insufficient archaeological data.

Considering the current evidence for iron production in this region, two production stages (smelting and forging) were conducted on a different spatial organisation. Iron smelting seems to have exclusively been carried out at some locations, whereas forging/repairing of objects may have taken place more frequently at habitation sites, as suggested by finds of smithing slag in most Iron Age habitation sites in lower Northeast Thailand, and from which the fallacy of "abundance" iron smelting derives (Figure 4.4 and 9.2). This suggests that smelters were attached to specific settlements, while blacksmiths were dispersed in villages. The concentration of smelters in some communities may correspond to a comparatively more technologically complex nature of the smelting activity compared to forging or that their locations close to ore deposits. The former is partly demonstrated by complex process of laterite smelting in Ban Kruat.

Focusing on the smelting contexts, activity was identified both with habitation areas (STH8, Non Malai, Ban Dong Phlong, and Ban Krabueng Nok) and at dedicated sites

(KDT2) (see sections 4.3.1.1 and 6.3.1). The question remains as to how a specific community was able to participate in this smelting. One possibility is that smelting technology was brought by new settlers from nearby locations (expansion of communities) (see section 9.2.3.1). Variability of smelting traditions in lower Northeast Thailand (see section 9.2.2.2) suggests that different practices were formulated to extract iron from acquired ores. In the same region, there seems to be no indication of nucleated production (i.e. production close to a resource) (White and Pigott 1996, 168; cf. Costin 1991, 14). This is probably due to the availability of laterite in wide area of lower Northeast Thailand and, probably, the presence of small deposits of typical iron ores, which would not have restrained the workshops to concentrate on specific areas (see section 3.2 and 6.2), unlike the exploitation of copper, tin, and lead (Pryce 2014). This possibly allowed locals to acquire iron from nearby production communities and transformed the acquired billets into desired objects at their own settlements. Moreover, this dispersion of ore resources may have prevented an effective control over the production and resources. During the Iron Age of lower Northeast Thailand, the society had moved toward increasingly hierarchical which gradually saw a rise of chiefdoms (Higham 2012, 2015). As introduced earlier, it is hypothesised that these elites/chiefs sought to control strategically socioeconomic activities (e.g. exchange networks and water conservation) from which they could generate wealth from (O'Reilly 2014). Craft production, including iron production was another sector that could have potentially been controlled; however, archaeological evidence from this region seems to suggest that there is no clear tight control over craft production or specific resources (White and Pigott 1996 and see sections 3.3.2.1 and 3.3.2.2).

The iron production sites, which are not highly nucleated (see Figure 4.4 and 9.2) suggest that the production may have been organised in non-centralised and multi-centred manner. Each workshop is likely to have served a limited number of nearby non-iron-producing communities. Iron from each workshop may have circulated within this limited sphere, which could eventually be tested by iron provenance studies in the future. The multiple production sites would not have allowed local elites to seek control and generate significant levels of wealth from this production. However, this production and its product exchange could still have been considered within a political strategy (Earle 1991, 5, 1997, 7), but with lesser efficacy, since the technology was still possessed by some communities. Raw iron may not have been prestige goods but more of utilitarian (Brumfield and Earle 1987, 6-7), regardless of its strategically economic value. However, elites may still have participated in this activity to some extent, particularly in terms of mobilisation of labour, similar to what is argued for the construction of moats and water conservation (O’Reilly 2014 and see section 3.3.2.1). The reconstruction of Ban Kruat smelting production suggests that this activity was laborious and that the workload in producing iron was significant. To achieve this, it may have needed a mechanism to mobilise the community to assist in ore preparation and smelting processes.

In sum, without tight control over production by a local authority, iron production could be categorised as independent specialised production, where it served varying demand from the overall population rather than elites only (Costin 1991, 11). Metalworkers, since they were not sponsored, are likely to have still been required to participate in subsistence production. Therefore, iron may have been produced seasonally outside the agricultural cycle. Evidence from KDT2 is still not clear enough to suggest whether the episodic activities were consecutive without interruption or the result of seasonal activities. On this basis, organisation of iron production in lower Northeast Thailand, including Ban Kruat may likely represent community-based specialisation (White and Pigott 1996).

This interpretation ties in the models of organisation of other craft production in Northeast Thailand which has argued that the independent specialised production (bronze and Phimai black pottery) was carried out at multiple locations and not fully controlled or sponsored by elites (Geary 2012; White 1995; White and Pigott 1996). Rather than controlling ironmaking, control of water, land, and exchange of goods and intra- and interregional exchange networks, particularly those of foreign origin (e.g. imported raw copper, tin, lead, and exotic ornaments) tended to be more effective political strategies that could have allowed local elites to sustain their power and compete with others (Higham 2014; O’Reilly 2014).

9.3.2 Contextualising Ban Kruat iron production in the context of Angkorian Khmer Empire (9th-15th century AD)

Although the temporal affiliation of Ban Kruat slag sites to the Angkorian period has yet to be securely confirmed by direct dates, other contemporary evidence (e.g. monumental, production, and artistic remains) correspond neatly to this period. In the wider picture, iron was in great demand by the empire as a medium to fuel wealth-generating sectors, particularly those related to agriculture, which the Khmer economy relied on. This in return sustained the ruling power of elites in the hierarchical political system of Angkor and maintained the empire’s stability. The wealth and political stability generated would allow the empire to grow from its original stronghold in the Great Lake plain in Cambodia to occupy and hold its western territories, including lower Northeast

Thailand (see sections 3.3.4.2 and 4.3.2). The production remains found inside a walled complex of Preah Khan of Kompong Svay (PKKS) may suggest a tightly-controlled state-sponsored iron production; although, this evidence represents a production during the terminal period. There was a technological change to better respond to an increase of demand for iron. The proximity of this site to ore deposits at Phnom Dek (PD), which was home to iron Kuay, skilled iron smelters, also represents an Angkorian attempt to maintain a supply network of iron from the independent Kuay smelters (Pryce *et al.* 2014).

In Ban Kruat production, relative dating tentatively links some slag deposits to this period. It is intriguing to wonder what kind of organisational approach was employed, and how it compared to those observed at PKKS and PD. Two possible scenarios of organisation of production are envisaged based on associated social contexts (see sections 3.3.4 and 4.3.2), which can be tested by new findings from this current study. The first scenario hypothesises that new sets of technology and metalworkers were introduced to Ban Kruat in hope to improve the productivity. The second scenario sees that the old tradition had been continued while the empire only acquired a constant supply of iron, possibly representing a focus on the product rather than the process (see section 4.3.5.2 for a detailed discussion).

If the continuity in iron production to this period, as presented above, is accepted, the second scenario is then favoured. While new technologies (e.g. irrigation (baray), glazed ceramic production, and sandstone/laterite quarries) were introduced to Ban Kruat, this was not the case for iron production. Preceding ironmaking traditions from laterite were preserved unaltered. Again, local geochemistry of the laterite ore and a need to strictly control the specific furnace operation may have been major constraints that made the introduction of new technologies or practices very difficult (see section 9.2.3.2).

Thus it would appear that only the organisational mechanism was changed, but not the materials and techniques. As argued in section 3.3.4.2, the temple-based economic network may have been a prominent mechanism administering production and products. While more data are needed, it is hypothesised that local (village) temples in Ban Kruat were responsible for organising all types of production. Smelters and labourers would probably be drawn from the immediate region, would be part of this learning and smelting tradition, resulting in a standardised production. The majority of the product may have been circulated among the settlements in lower Northeast Thailand or sent to the larger administrative centres, such as Muang Tam and Phimai (see section 3.3.4.1.1). This would have then been consumed by various sectors, particularly agriculture. Some may have been sent to the royal storage at the capital, which with iron from other production, would be circulated within the empire (see section 4.3.2). Although this is obviously a working hypothesis, an ongoing project "IRANGKOR", which aims to study the production, trade, and consumption of iron in the Angkorian period, may help elucidate how iron from Ban Kruat was distributed within the empire (Leroy pers. comm. 3 March 2015).

The interpretation also contributes to understand the local archaeology. Established iron smelting and, possibly, steel-making tradition could have attracted the Khmers to incorporate this area into the Angkorian realm, and this production would have benefitted and sustained the Khmer expansion to the West. The production scale might have been increased to meet demand, possibly in the 12th century AD when Khmer ceramic production was established in Ban Kruat. This area was thus likely transformed into an industrial zone, potentially to support the power struggle of the Mahindhrapura royal dynasty, whose initial political power was in lower Northeast Thailand (Suksvasti 1990, 42-44). This metal industry, as well as ceramic production, probably continued for a long period. The decline may have on started with the decline of Angkor in the 15th century AD and the later relocation of people to new towns by Siamese authorities in 16th-20th century AD (Briggs 1948; Chandavij and Chandavij 1989, 13; Prommanoj 1989, 19; Vickery 2004).

9.4 Identifying choices and constraints on Ban Kruat laterite smelting technology – final thoughts

As technical and social dimensions of Ban Kruat iron production were explored throughout Chapters 8 and 9 in conjunction with broader contexts of archaeology of lower Northeast Thailand and archaeometallurgy of iron production in Thailand, it is possible to suggest choices and constraints involved in this laterite smelting – why Ban Kruat smelters needed to follow this technological trajectory and to what extent they might have other choices in making iron in Ban Kruat.

Evidently, without a definitive site chronology and associated social contexts, it is not possible to fully understand all factors and influences behind the different choices made by local smelters. In any case, this thesis has shown that, as far as the currently available data show, geological constraints (e.g. types of ores smelted and accessibility to those ores) seem to have played the most crucial role in shaping this smelting technology.

Specific set of practices was formulated in order to win iron from this iron-poor, crumbly ore. This geological constraint left little room for variation or improvement. Due to this, very similar practices had been preserved for a long period of time. On this basis, there may have been little choice available to local smelters, unless they were to import high quality ore from further afield. This latter option, even though considered a typically uneconomic solution, is still possible and cannot be ruled out. Archaeology of lower Northeast Thailand has already illustrated that throughout the periods from the Iron Age to the Angkorian period, this region was well connected with neighbouring areas where standard ores were available such as Central Thailand, Cambodia, Laos, or even small typical iron ore deposits in the western part of Northeast Thailand. The lead isotope analysis of copper and lead has also shown that both metals were imported into lower Northeast Thailand through the existing trade networks. Therefore, iron ores could have also been flown into this region. However, there has been so far no evidence of the use of standard ores in iron smelting in Ban Kruat, and chemical data of Ban Kruat smelting slag seems to disagree with this possibility.

Another possibility of how to improve this smelting technology in light of strict source of ore may concern the specific selection of high-grade laterite nodules which may have contained high levels of iron oxide, similar to standard ores. One laterite nodule sample (STH8e004) contains iron oxide 76 wt% and alumina 8 wt% (see Table 8.3) which is arguable similar to haematite and limonite. Smelting this kind of laterite may have no longer needed very high reducing conditions, and the smelters could have had more choices in operating the furnace. However, the analytical result of smelting slag again has not shown any indication to support the specific selection of such ore.

As demonstrated earlier, smelting laterite requires different adjustments of the furnace conditions from what used for smelting standard ores. The main problem lies in the chemical inconsistency of this ore, quite different from working with standard ores. If one views this laterite smelting technology as local adjustment of preceding typical iron ore smelting technology, it is highly possible that early smelters may have needed to explore various variables in order to cope with this new and chemically varied kind of iron ores. Smelters may have been to reconsider how to operate the furnace for each batch of ore, and the later solution seen in Ban Kruat practice was by employing high temperatures and very high reducing conditions for every smelt. Developing this solution, various smelting settings may have been experimented, including operational temperature, supply of air, and charcoal:ore ratio. Future experiments of laterite smelting compared to typical iron smelting may help clarify what variables need to be considered.

While the environmental factors seem thus understood, social constraints on production remain unclear for why local smelters needed to accept this technology. Rather, the society may have had to embrace this technology in order to secure a local supply of iron when typical iron ores were unavailable. In actuality, the technology was reasonably efficient in recovering iron from the ore. The system may have also offered steel directly from the smelting process, which was not a common product of bloomery smelting. This special feature may have been recognised by the markets. Although steel is harder to forge, it possessed greater durability than soft iron and was thus better suited to certain types of tools and weapons.

Although this technology offered iron to local communities, it is likely to have more or less posed some pressure on local economy. As the process was likely to have been time and labour-intensive (e.g. sorting laterite nodules, making charcoal, and operating furnaces), available workforce may have needed to be drawn from other sectors such as construction and agriculture. In the Iron Age, the labour organisation may have still been manageable as the activity was possibly run after the agricultural season. However, it might become more problematic for the production during the Angkorian period when the whole region was transformed into the industrial landscape where more labourers were highly demanded by various industries (e.g. ceramic production, quarry, and iron smelting) as well as agricultural and construction sectors.

Owing to this, socioeconomic constraint seems to have been the main issue allowing this technology to remain in this region. To what extent social beliefs may have perpetuated this technology likewise Kasungu iron smelting (see section 9.2.2) is very difficult to be examined with current data, and Ban Kruat has still lacked of any evidence for social beliefs in association with iron smelting. Ethnographic evidence only suggests that ritual practice in iron smelting is done to please spirits which, in return, would ensure the successful outcome.

9.5 Contribution to the understanding of the social development of Ban Kruat

This very last section is hoped to bring all findings and interpretations in this thesis to improve our understanding of the social development of Ban Kruat through the study of technology.

Current archaeological evidence suggests that Ban Kruat was occupied before the earliest dated smelting context (ca. AD200) (see section 7.3.1.1), possibly at some point between 100BC-AD200, according to the presence of Phimai black pottery (see section 3.3.2). The founding of settlements in this area may have been a response to a need of new resources, which stimulated an expansion of Iron Age communities from the floodplains, possibly both in lower Northeast Thailand and Northwest Cambodia to terrace and upland zones, including Ban Kruat. The migrants brought material culture and knowledge with them and kept contact with their origins through expanding intra- and interregional exchange networks. This resulted in a similarity in material culture between Ban Kruat and other communities in lower Northeast Thailand (Higham 2012, 2014) and Northwest Cambodia (O'Reilly 2003; O'Reilly *et al.* 2004, 2006), particularly those residing in upper Mun River valley (see Chapters 3 and 6). The early activities at STH8 and Ban Bueng Noi saw habitation and mortuary practices with possibly very small scale iron production. From ca. AD200, iron production became a main activity creating a distinctive feature of slag mounds. The origin of iron smelting may have been transmitted from outside Ban Kruat but through time it had developed to cope successfully with local geochemistry of laterite ore and clay. As a result, the technology became quite idiosyncratic and distinguishable from other practices in Thailand and, possibly, others in mainland Southeast Asia. By this point, local smelters probably had mastered the practice. The production probably served a demand of the settlements in lower Northeast Thailand and possibly those located across into Cambodia.

In the transition period (AD500-802) from later Prehistory to the Angkorian period, there is no secure evidence for Ban Kruat's occupation. It was not until the 11th century AD that Khmer culture was introduced, including new technologies, such as monumental architecture, reservoirs, and sandstone and laterite quarrying. The preceding ironmaking tradition had been preserved and practised without modification by other Angkorian period ironmaking traditions. The production had been carried out in parallel with prominent Khmer ceramic production. The productions were possibly supervised by local temples, which may have channelled the products to other administrative centres and settlements in this western territory rather than transporting all produced iron to Angkor. The existence of these productions may have been recognised as a political strategy by regional elites and Angkorian kings alike as one approach to generate wealth from local resources. This wealth would then have been fuelled civil and military campaigns that maintained the political power of Angkor over its subordinates. The decline and termination of the productions may have occurred at the time when regional political power was shifting to central Thailand. This rendered this part of lower Northeast

Thailand insignificant, and the local population was later relocated to new strategic towns.

Chapter 10 Conclusion

Previous studies on metallurgical remains in Ban Kruat already hinted at the significance of this area as an ancient iron smelting in the archaeological context of lower Northeast Thailand (Lertlum *et al*. 2008; Yoopom 2010). This area has hitherto exhibits the highest concentration of iron production remains in Thailand, and research attention was warranted. The contribution of these studies to characterising the broader cultural and technological landscape of lower Northeast Thailand was limited, however, by the limited scope of excavations and materials study, uncertainties in chronology, and a lack of specialist studies; thus many questions remained to be addressed (see Chapter 7).

In light of this, this thesis aimed to improve our understanding of Ban Kruat iron production in terms of its technological and social dimensions, and its place in a broader cultural landscape of lower Northeast Thailand. A series of archaeological and archaeolometallurgical approaches were employed to investigate the metallurgical remains found at 47 slag mounds in order to draw a substantial body of technical data (see Chapters 5 and 7). Guided by the interpretative frameworks of the social construction of technologies, including the concept of *chaîne opératoire* (see Chapter 2), an improved reconstruction of ironmaking activities in Ban Kruat has been developed (see Chapters 8 and 9), providing significant revisions to previous efforts (Chuenpee *et al*. 2014; Venunan 2011; Yoopom 2010) and addressing specific technical questions. Constraints that crucially shaped said technology were also identified and explained. Ban Kruat *chaîne opératoire* was then contextualised with reference to models of craft production and a revised chronological framework of lower Northeast Thailand (between the Iron Age (500BC-AD500) to the Angkorian Khmer period (AD802-1453)) (see Chapter 2-4 and 6).

By and large, it is felt that the research has fulfilled the aim and objectives spelled out in the introductory chapter. The findings and their technical and social significance were extensively presented and summarised in Chapters 8 and 9. This concluding chapter will highlight the relevance of this thesis in a wider archaeological and archaeometallurgical contexts, and the effectiveness of the methods employed in illuminating both technical and social aspects of one of the most important crafts in the political and socioeconomic development of lower Northeast Thailand during the periods concerned.

This thesis may be considered one of very few (e.g. Nitta 1991, 1996, 1997; Pryce 2008; Suchitta 1983) that engages the potential of combined applications of archaeology and archaeometallurgy for revealing technical and social histories in Thailand. The work presented here combined different approaches: an extensive and critical literature review, fieldwork including survey and excavation, field and laboratory analyses, and cross-comparative study of Ban Kruat metallurgical remains in order to properly obtain technical data and translate them into social meaning. At the beginning of this thesis, it was argued that archaeological evidence from Ban Kruat alone would not allow a contextualised social history of iron production. In order to tackle this challenge, it was necessary to compile and review a large body of archaeological knowledge from a higher geographical span that embraced Ban Kruat environmentally and socially (lower Northeast Thailand, central Thailand, and Northwest and Tonle Sap plain of Cambodia). Integrated archaeological data were employed to fill the missing gaps where Ban Kruat could not offer the necessary information at the moment of writing. This analysis of previous work in the broader region also allowed this thesis to review our knowledge of ancient craft production, which served as a basis for constructing hypothetical models for iron production. This was a crucial step for this thesis, given the lack of dedicated working models that could be tested by the newly generated data from Ban Kruat. Even if this thesis could not provide a definitive, high-resolution contextualisation in all possible dimensions, the models presented can still be considered when more data become available. This will hopefully help prevent aprioristic assumptions and oversimplistic approaches to iron technologies in the region.

Direct involvement in the fieldwork campaigns and subsequent site visits for sampling allowed a better understanding of spatial, stratigraphic and morphological features of the sites, ensuring extensive sampling of metallurgical remains from other slag sites in addition to what was already available from the previous LARP excavations. A survey was able to preliminarily investigate the metallurgical remains, particularly slag, in order to obtain an initial view of the production landscape that could be evaluated by further detailed laboratory analysis.

Lastly, the comparative study proved to be a very powerful approach allowing a better technical and social interpretation of the newly generated data. Various case studies were drawn not only from mainland Southeast Asia, but also from Europe and Africa. These “external” data helped add other information that could not have been addressed focusing narrowly on Ban Kruat technical and archaeological data only. Reference to these studies facilitated the reconstruction of the *chaîne opératoire* of Ban Kruat iron production on various issues, such as slag liquidus temperature, reduction mechanism, iron formation, the exploitation method of laterite, and air supplying method – while also making it easier to highlight the singularities of the Thai case.

The integration of different sets of knowledge into a reconstruction of ancient iron production in Ban Kruat has been successful in allow a substantially renewed picture of iron technology and its environmental and social adaptations that offers a contribution to the archaeology and archaeometallurgy of lower Northeast Thailand and beyond, as summarised in the previous chapter. This research contributes directly to a long debate on the use of laterite as an ore in lower Northeast Thailand. Despite the fact that there were previous attempts in tackling this issue (Cawte and Boyd 2010; Pryce and Natapintu 2007), this current research is considered the first to bring together all associated archaeometallurgical and archaeological findings allowing the author to ascertain that laterite was indeed smelted, at least in Ban Kruat. Besides this major contribution, this thesis methodologically developed a number of diagnostic criteria to facilitate the characterisation of iron technologies in other regional contexts. Although a more systematic database of ore and slag in the region is still needed, some structural and chemical markers can potentially be used for a preliminary discrimination between non-laterite and laterite smelting. In particular, amorphous slag lumps without obvious flowing texture and high alumina levels may be deemed as important markers of the iron smelting tradition revealed at Ban Kruat, ideally to be further substantiated with more detailed microanalyses. It is hoped that this study will also raise awareness among archaeologists working with iron production remains in lower Northeast Thailand that not all slag can be defined as smelting slag, and that laterite may not have been the only ore smelted in this region. Moreover, received wisdom that iron smelting was a widespread activity needs to be reconsidered.

Potential further work

Throughout this thesis, an attempt has been made to acknowledge dimensions where obvious gaps in relevant archaeological data prevented conclusive claims or interpretations. Although this study was able to shed new light on this local industry and the social role of the production in regional archaeology, many questions were left inevitably unanswered, or addressed only on speculative grounds – with the expectation that future work will test them. Based on the models presented in this thesis, some questions and current interpretations could be addressed and improved by bringing in new data that can be generated through future archaeological works.

One of the important tasks to follow this thesis is the identification of secure metallurgical contexts for the two missing periods: the transition period (AD500-802) and the Angkorian Khmer period (AD802-1453). This is essential to confirm the hypothesis that iron production continued into the later periods. Two potential sites: NC4 and STH8 cluster are worth being resurveyed and excavated as archaeologically-attested Khmer ceramic fragments were found on them. The future study on STH8 may also clarify the formation processes for the 11 slag mounds, including to what extent they were formed in the same period or separately. However, the further study on slag mounds in Ban Kruat is indeed a work against time. During the past 10 years, Ban Kruat has seen a constant demolishing of slag mounds or deposits. In 2005-2007, 67 slag sites were documented, but only 47 slag sites remained when the author revisited the area in 2012. In early 2015, more slag sites, including the STH8 cluster, which was the best preserved slag group in Ban Kruat, were also found partly demolished, but the future works can still benefit from this unfortunate event as some datable pottery fragments could be brought up to the surface.

Besides archaeological excavation, and a better resolved chronology at the site level, slag inclusion analysis (i.e. slag trapped in iron artefacts) (Blakelock *et al*. 2009; Biggs *et al*. 2013) may help clarifying the existence of iron production activities belonging to later periods, particularly the Angkorian Khmer period. The analysis of smelting suggested that slag could be divided into TiO_2-poor and TiO_2-rich. It may be possible to use this TiO_2-rich signature, along with other meaningful non-reduced elements, as an indicator when studying slag inclusion remaining in well-dated iron artefacts. Slag inclusions analyses will also be useful to map the extent of the distribution of Ban Kruat iron and hence inform about relationships between producers and consumers in lower Northeast Thailand and its neighbouring areas, including Cambodia. Furthermore, the metallographic study, combined with slag inclusions, will also be useful in ascertaining whether Ban Kruat was making steel.

As proposed above, the creation of a slag and ore chemical database would not only aid slag inclusion studies, but generally constitute a valuable resource to better understand iron technologies and their technical variability of lower Northeast Thailand, as well as to help confirm if high alumina can be used as a proxy for the use of laterite as an ore. It is suggested that microanalysis of selected samples should always be performed where possible. As demonstrated by this thesis, more information, such as microstructure, redox condition, and grain size of the ore, which was essential to this thesis's reconstruction, can be obtained. It is also hoped that palaeoenvironmental studies and fuel ash composition analyses may be available in the future; this will facilitate an improvement of mass balance calculations, and help identify the species of wood used for charcoal making, hence contributing to both the resolution of our technical inferences and the contextualisation of iron technologies in their environment.

While constrained by inevitable limitations and leaving plenty of scope for future work, it is believed that this thesis has succeeded in addressing the aims proposed and justified at the beginning, and hoped that it will pave the way for future studies of archaeometallurgy and craft organisation in the broader region.

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Appendices

Appendix A SEM-EDS analysis of CRMs

	Na_2O (wt%)	Al_2O_3 (wt%)	SiO_2 (wt%)	K2O (wt%)	CaO (wt%)	TiO_2 (wt%)	MnO (wt%)	FeO (wt%)	Original analytical totals (wt%)
Normalised reference values	0.64	7.76	25.82	1.03	1.52	0.32	3.27	59.63	95.76
Measurements (normalised)									
1	0.9	7.6	24.6	1.3	1.7	0.3	3.1	60.5	88.8
2	1.1	8.3	24.0	1.4	1.8	0.4	3.2	59.9	88.9
3	1.0	7.5	23.4	1.3	1.6	0.3	3.5	61.3	86.0
4	1.0	7.4	23.9	1.3	1.5	0.3	3.1	61.5	86.5
5	1.2	7.6	24.4	1.2	1.6	0.4	3.5	60.1	91.1
6	1.0	7.6	24.8	1.2	1.7	0.2	2.9	60.7	90.0
Mean	1.0	7.7	24.2	1.3	1.6	0.3	3.2	60.6	
Precision									
Standard deviation	0.1	0.3	0.5	0.1	0.1	0.1	0.2	0.6	
Coefficient of variation (%)	17	4	2	8	6	17	7	1	
Accuracy									
Absolute error	0.4	-0.1	-1.6	0.2	0.1	0.0	1.0	0.4	
Relative error	63.4	-0.9	-6.3	23.9	7.8	-1.1	1.6	63.4	

Precision and accuracy test of SEM-EDS using Swedish slag (Kresten and Hjärthener-Holdar 2001). MgO, P_2O_5, MnO, and trace elements reported in the publication were not measured.

	Na_2O (wt%)	MgO (wt%)	Al_2O_3 (wt%)	SiO_2 (wt%)	K2O (wt%)	CaO (wt%)	TiO_2 (wt%)	FeO (wt%)	Original analytical totals (wt%)
Normalised reference values	2.25	7.33	13.69	50.61	0.53	11.56	2.77	11.26	98.60
Measurements (normalised)									
1	2.2	6.9	13.4	51.1	0.5	11.8	2.7	11.4	97.8
2	2.4	7.0	12.9	50.5	0.5	12.0	3.0	11.6	98.1
3	2.4	7.2	13.1	51.1	0.6	11.7	2.9	11.1	98.8
4	2.3	7.1	13.0	50.7	0.6	11.7	3.0	11.6	98.5
5	2.7	7.0	13.0	51.1	0.5	11.8	2.7	11.2	99.9
6	2.4	7.5	13.1	51.1	0.5	11.4	2.8	11.2	99.9
Mean	2.4	7.1	13.1	50.9	0.5	11.7	2.9	11.3	
Precision									
Standard deviation	0.2	0.2	0.2	0.2	0.0	0.2	0.1	0.2	
Coefficient of variation (%)	7	3	1	0	6	2	4	2	
Accuracy									
Absolute error	0.2	-0.2	-0.6	0.3	0.0	0.2	0.1	0.1	
Relative error	-6.9	3.1	4.4	-0.6	-1.6	-1.4	-3.0	-1.0	

Precision and accuracy test of SEM-EDS using BHVO-2, Basalt, Hawaiian Volcanic Observatory (USGS 1998b). P_2O_5 and trace elements reported in the publication were not measured.

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K2O	CaO	TiO_2	FeO	Original analytical totals
	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)
Normalised reference values	3.22	3.65	13.74	55.05	0.36	1.82	7.24	2.30	12.63	98.28
Measurements (normalised)										
1	3.3	3.5	13.0	55.6	0.4	1.8	7.4	2.3	12.6	99.1
2	3.3	3.7	13.1	55.7	0.3	1.9	7.2	2.3	12.7	99.6
3	3.3	3.3	13.0	55.4	0.4	1.9	7.4	2.5	12.7	98.5
4	3.2	3.6	12.9	55.9	0.4	1.7	7.4	2.3	12.6	98.5
5	3.3	3.7	13.1	55.2	0.6	1.8	7.4	2.2	12.8	99.5
6	3.6	3.6	12.8	55.9	0.5	1.7	7.2	2.4	12.2	99.4
Mean	3.3	3.6	13.0	55.6	0.4	1.8	7.3	2.4	12.6	
Precision										
Standard deviation	0.1	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.2	
Coefficient of variation (%)	4	4	1	1	26	4	2	5	2	
Accuracy										
Absolute error	0.1	-0.1	-0.8	0.6	0.1	0.0	0.1	0.1	0.0	
Relative error	3.4	-2.1	-5.5	1.0	15.0	-0.9	1.1	2.5	-0.2	

Precision and accuracy test of SEM-EDS using BCR-2, Basalt, Columbia River (USGS 1998a). Trace elements reported in the publication were not measured.

	Na_2O	MgO	Al_2O_3	SiO_2	K2O	CaO	TiO_2	FeO	Original analytical totals
	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)
Normalised reference values	1.92	1.95	14.08	70.67	2.82	3.43	0.70	4.43	94.30
Measurements (normalised)									
1	1.9	2.5	16.6	64.9	3.2	3.9	0.9	6.3	82.7
2	2.0	2.5	16.2	65.2	3.2	4.1	0.9	6.0	81.7
3	1.7	2.7	16.3	64.4	3.3	4.3	0.8	6.4	82.8
4	1.9	2.5	16.2	65.3	3.2	4.0	0.6	6.4	81.3
5	2.0	2.5	17.0	65.3	3.2	3.8	0.7	5.5	83.0
6	1.9	2.5	16.5	64.9	3.3	4.4	0.8	5.9	82.2
7	1.8	2.6	16.7	64.2	3.3	4.2	0.8	6.4	83.5
Mean	1.9	2.5	16.5	64.9	3.2	4.1	0.8	6.1	
Precision									
Standard deviation	0.1	0.1	0.3	0.4	0.1	0.2	0.1	0.3	
Coefficient of variation (%)	6	4	2	1	2	5	13	6	
Accuracy									
Absolute error	-0.1	0.6	2.4	-5.9	0.6	0.7	0.1	1.7	
Relative error	-3.6	29.4	17.1	-8.4	21.6	19.2	10.5	38.3	

Precision and accuracy test of SEM-EDS using NCS Clay DC60105 (China National Analysis Centre). Cl, SO_3, P_2O_5, and MnO reported in the publication were not measured.

	MgO	Al_2O_3	SiO_2	K2O	TiO_2	FeO	Original analytical totals
	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)	(wt%)
Normalised reference values	0.53	39.13	55.51	1.34	2.05	1.46	98.90
Measurements (normalised)							
1	0.5	37.8	55.8	1.5	2.3	2.2	84.8
2	0.3	37.6	56.0	1.5	2.5	2.1	85.7
3	0.5	37.7	56.1	1.4	2.3	1.9	87.7
4	0.4	38.0	56.5	1.3	2.0	1.8	86.8
5	0.5	38.0	56.1	1.5	2.3	1.6	86.9
6	0.6	38.4	55.7	1.4	2.1	1.9	85.7
Mean	0.5	37.9	56.0	1.4	2.3	1.9	
Precision							
Standard deviation	0.1	0.3	0.3	0.1	0.2	0.2	
Coefficient of variation (%)	19	1	1	6	9	10	
Accuracy							
Absolute error	-0.1	-1.2	0.5	0.1	0.2	0.5	
Relative error	-11.6	-3.1	0.9	6.1	9.8	31.7	

Precision and accuracy test of SEM-EDS using NIST 76a Burnt Refractory (NIST 1992). Na_2O, P_2O_5, CaO, Li_2O, and SrO reported in the publication were not measured.

	Na_2O (wt%)	MgO (wt%)	Al_2O_3 (wt%)	SiO_2 (wt%)	K2O (wt%)	CaO (wt%)	ZnO (wt%)	SrO (wt%)	CdO (wt%)	BaO (wt%)	PbO (wt%)	Original analytical totals (wt%)
Normalised reference values	5.18	5.18	8.31	46.85	4.58	5.01	4.95	5.03	4.84	5.16	4.86	
Measurements (normalised)												
1	6.0	5.0	7.8	47.2	4.0	5.1	4.9	4.6	5.2	5.1	5.2	89.0
2	5.9	4.5	8.0	47.5	4.4	4.9	4.7	4.9	4.9	5.2	4.9	90.5
3	5.5	4.8	8.0	46.4	4.1	5.3	5.6	4.8	5.2	5.0	5.3	92.2
4	6.1	4.6	8.0	47.1	4.5	5.0	5.1	4.3	5.0	5.2	5.2	91.4
5	6.0	4.9	7.9	46.2	5.0	5.0	4.9	5.0	4.7	5.4	4.9	90.3
6	5.9	4.8	8.0	47.4	4.3	4.9	5.1	4.7	4.6	5.2	4.9	91.4
7	5.5	4.7	7.5	47.4	4.4	5.2	4.7	5.1	5.0	5.5	4.9	90.6
8	5.4	4.9	8.1	46.8	4.9	5.0	4.9	4.5	5.0	5.5	5.1	91.7
9	5.9	4.9	8.0	46.5	4.5	5.0	4.7	5.0	5.2	5.3	5.1	91.9
Mean	5.8	4.8	7.9	46.9	4.5	5.0	5.0	4.8	5.0	5.3	5.0	
Precision												
Standard deviation	0.3	0.1	0.2	0.5	0.3	0.1	0.3	0.3	0.2	0.2	0.1	
Coefficient of variation (%)	5	3	2	1	7	2	6	6	4	3	3	
Accuracy												
Absolute error	-0.6	0.4	0.4	-0.1	0.1	0.0	0.0	0.2	-0.1	-0.1	-0.2	
Relative error	-12	8	5	0	2	-1	0	5	-3	-2	-4	

Precision and accuracy test of SEM-EDS using NIST 1412, multi-component glass. FeO, Li_2O, and B_2O_3 reported in the publication were not measured. The low analytical totals are due to Li_2O and B_2O_3 could not be measured by the instrument.

Appendix B WD-XRF analysis of CRMs

	Na_2O (wt%)	MgO (wt%)	Al_2O_3 (wt%)	SiO_2 (wt%)	P_2O_5 (wt%)	SO_3 (wt%)	K_2O (wt%)	CaO (wt%)	TiO_2 (wt%)	V_2O_5 (wt%)	Cr_2O_3 (wt%)	MnO (wt%)	FeO (wt%)	SrO (wt%)	ZrO_2 (wt%)	BaO (wt%)	La_2O_3 (wt%)	CeO_2 (wt%)	Original analytical totals (wt%)
Normalised reference values	0.63	0.42	7.67	25.53	0.27	0.10	1.02	1.51	0.32	0.03	0.01	3.23	59.12	0.01	0.01	0.08	0.01	0.03	96.89
Measurements (normalised)																			
10/04/2014	0.86	0.28	7.95	22.73	0.25	0.14	1.02	1.29	0.25	0.03	0.02	3.19	61.78	0.01	0.02	0.11	0.02	0.05	90.20
18/11/2014	0.85	0.27	7.88	22.82	0.24	0.13	1.03	1.32	0.25	0.02	0.01	3.14	61.86	0.01	0.02	0.12	0.01	0.03	90.20
Mean	0.86	0.27	7.91	22.78	0.24	0.13	1.03	1.31	0.25	0.03	0.01	3.16	61.82	0.01	0.02	0.12	0.01	0.04	
Precision																			
Standard deviation	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	
Coefficient of variation (%)	2	0	1	0	4	5	1	1	0	24	30	1	0	4	0	2	18	39	
Accuracy																			
Absolute error	0.23	-0.15	0.24	-2.75	-0.02	0.03	0.00	-0.20	-0.07	0.00	0.00	-0.07	2.70	0.00	0.00	0.04	0.00	0.01	
Relative error	36	-35	3	-11	-9	30	0	-13	-22	-11	29	-2	5	46	23	51	47	16	

Precision and accuracy test of WD-XRF using Swedish slag (Kresten and Hjärthener-Holdar 2001)

	Na_2O (wt%)	MgO (wt%)	Al_2O_3 (wt%)	SiO_2 (wt%)	SO_3 (wt%)	K_2O (wt%)	CaO (wt%)	TiO_2 (wt%)	MnO (wt%)	FeO (wt%)	Original analytical totals (wt%)
Normalised reference values	0.38	12.11	9.50	35.26	3.11	0.50	36.99	0.38	0.85	0.91	99.54
Measurement (normalised)											
10/04/2014	0.39	12.03	9.87	35.83	3.16	0.57	36.00	0.29	0.96	0.89	83.70
Accuracy											
Absolute error	0.01	-0.08	0.37	0.56	0.05	0.07	-0.99	-0.09	0.11	-0.02	
Relative error	2	-1	4	2	2	13	-3	-23	13	-2	

Precision and accuracy test of WD-XRF using SL-1 Blast Furnace Slag (NRCAN 2013)

	Na_2O (wt%)	MgO (wt%)	Al_2O_3 (wt%)	SiO_2 (wt%)	P_2O_5 (wt%)	K_2O (wt%)	CaO (wt%)	TiO_2 (wt%)	V_2O_5 (wt%)	Cr_2O_3 (wt%)	MnO (wt%)	Fe_2O_3 (wt%)	Original analytical totals (wt%)
Normalised reference values	2.21	7.21	13.46	49.73	0.27	0.52	11.36	2.72	0.06	0.04	0.17	12.26	100.33
Measurement (normalised)													
10/04/2014	2.48	5.40	16.45	48.77	0.26	0.51	10.69	2.24	0.08	0.06	0.18	12.88	86.80
Accuracy													
Absolute error	0.26	-1.81	2.99	-0.97	-0.01	0.00	-0.67	-0.48	0.03	0.02	0.01	0.62	
Relative error	12	-25	22	-2	-2	-1	-6	-18	48	50	9	5	

Precision and accuracy test of WD-XRF using BHVO-2 Basalt, Hawaiian Volcanic Observatory (USGS 1998)

	Na_2O (wt%)	MgO (wt%)	Al_2O_3 (wt%)	SiO_2 (wt%)	P_2O_5 (wt%)	SO_3 (wt%)	K_2O (wt%)	CaO (wt%)	TiO2 (wt%)	MnO (wt%)	Fe_2O_3 (wt%)	Original analytical totals (wt%)
Normalised reference values	0.09	2.35	5.78	10.04	1.09	1.36	0.43	30.67	0.22	1.70	46.27	73.69
Measurement (normalised)												
10/04/2014	0.10	1.97	6.54	10.12	1.04	0.62	0.43	26.25	0.22	1.76	50.96	82.90
18/11/2014	0.10	1.98	6.65	10.25	1.03	0.60	0.43	26.04	0.19	1.78	50.94	82.50
Mean	0.10	1.97	6.59	10.19	1.04	0.61	0.43	26.15	0.20	1.77	50.95	
Precision												
Standard deviation	0.00	0.01	0.08	0.10	0.00	0.01	0.00	0.15	0.02	0.01	0.01	
Coefficient of variation (%)	3	0	1	1	0	2	0	1	9	1	0	
Accuracy												
Absolute error	0.01	-0.37	0.81	0.14	-0.05	-0.75	0.00	-4.52	-0.01	0.07	4.67	
Relative error	8	-16	14	1	-5	-55	0	-15	-6	4	10	

Precision and accuracy test of WD-XRF using BCS-301/1 Lincolnshire Ore (BAS 2011)

	Na_2O (wt%)	MgO (wt%)	Al_2O_3 (wt%)	SiO_2 (wt%)	P_2O_5 (wt%)	K_2O (wt%)	CaO (wt%)	TiO_2 (wt%)	Fe_2O_3 (wt%)	SrO (wt%)	Original analytical totals (wt%)
Normalised reference values	0.07	0.52	38.88	55.16	0.13	1.34	0.22	2.04	1.61	0.04	99.58
Measurement (normalised)											
10/04/2014	0.06	0.63	39.22	54.83	0.12	1.34	0.21	1.73	1.81	0.05	86.90
18/11/2014	0.06	0.65	39.17	54.91	0.12	1.34	0.21	1.73	1.78	0.05	87.00
Mean	0.06	0.64	39.20	54.87	0.12	1.34	0.21	1.73	1.79	0.05	
Precision											
Standard deviation	0.00	0.01	0.04	0.06	0.00	0.00	0.00	0.00	0.02	0.00	
Coefficient of variation (%)	2	1	0	0	2	0	1	0	1	2	
Accuracy											
Absolute error	-0.01	0.12	0.31	-0.29	-0.01	0.01	-0.01	-0.31	0.18	0.01	
Relative error	-17	22	1	-1	-6	1	-5	-15	11	25	

Precision and accuracy test of WD-XRF using NIST76a Burnt Refractory (NIST 1992)

	Na_2O (wt%)	MgO (wt%)	Al_2O_3 (wt%)	SiO_2 (wt%)	P_2O_5 (wt%)	K_2O (wt%)	CaO (wt%)	TiO_2 (wt%)	Cr_2O_3 (wt%)	Fe_2O_3 (wt%)	BaO (wt%)	Original analytical totals (wt%)
Normalised reference values	0.49	0.48	29.43	63.08	0.06	2.93	0.31	1.63	0.02	1.44	0.12	99.49
Measurement (normalised)												
10/04/2014	0.43	0.49	30.18	61.79	0.06	3.16	0.36	1.49	0.04	1.80	0.21	79.10
18/11/2014	0.42	0.50	30.12	61.81	0.06	3.19	0.35	1.47	0.03	1.82	0.23	79.20
Mean	0.42	0.49	30.15	61.80	0.06	3.17	0.35	1.48	0.03	1.81	0.22	
Precision												
Standard deviation	0.01	0.00	0.04	0.01	0.00	0.02	0.00	0.01	0.00	0.01	0.02	
Coefficient of variation (%)	2	1	0	0	2	1	0	1	12	1	7	
Accuracy												
Absolute error	-0.07	0.02	0.72	-1.28	0.00	0.24	0.04	-0.14	0.01	0.37	0.10	
Relative error	-14	3	2	-2	1	8	14	-9	47	26	80	

Precision and accuracy test of WD-XRF using BCS776-1 Firebrick (BAS 1983)

Appendix C Metallurgical sites: locations, evidence, and current condition

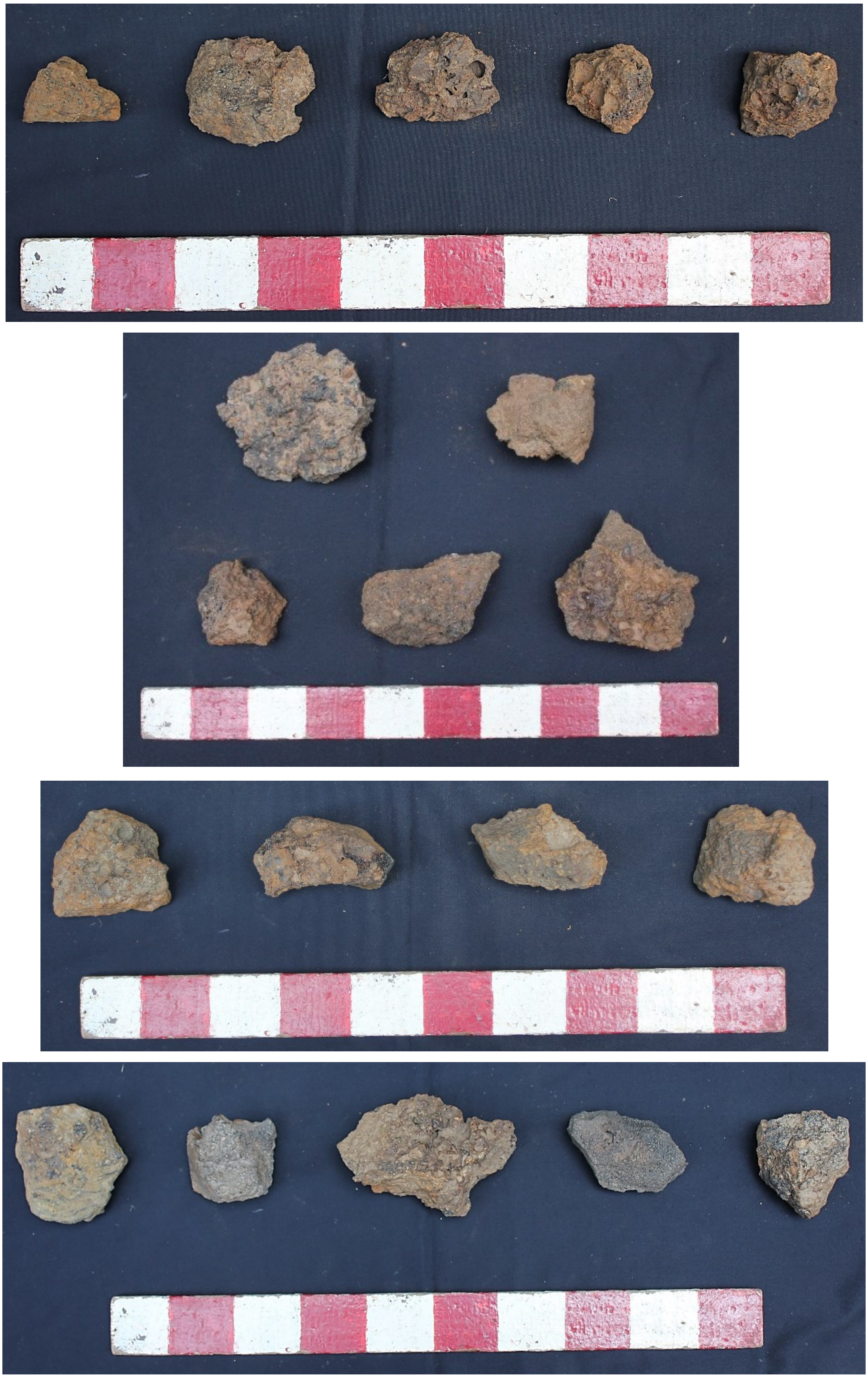
<u>Ban Khok Yang, Ban Kruat subdistrict, Ban Kruat district</u>

Sites	Site code in FAD1989/ FAD2008	Coordinates (Decimal degrees)	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Note
KY1	-	14.46467 103.10256	Small-sized and light slag	Slag 5	-	Demolished, rice field
KY2	F#30	14.4635 103.103	Small-sized and light slag	-	-	Demolished, rice field
KY3	F#31	14.4633 103.1025	Small to medium-sized, light to heavy, porous and dense slag	Slag 5	-	Slag found next to the kiln

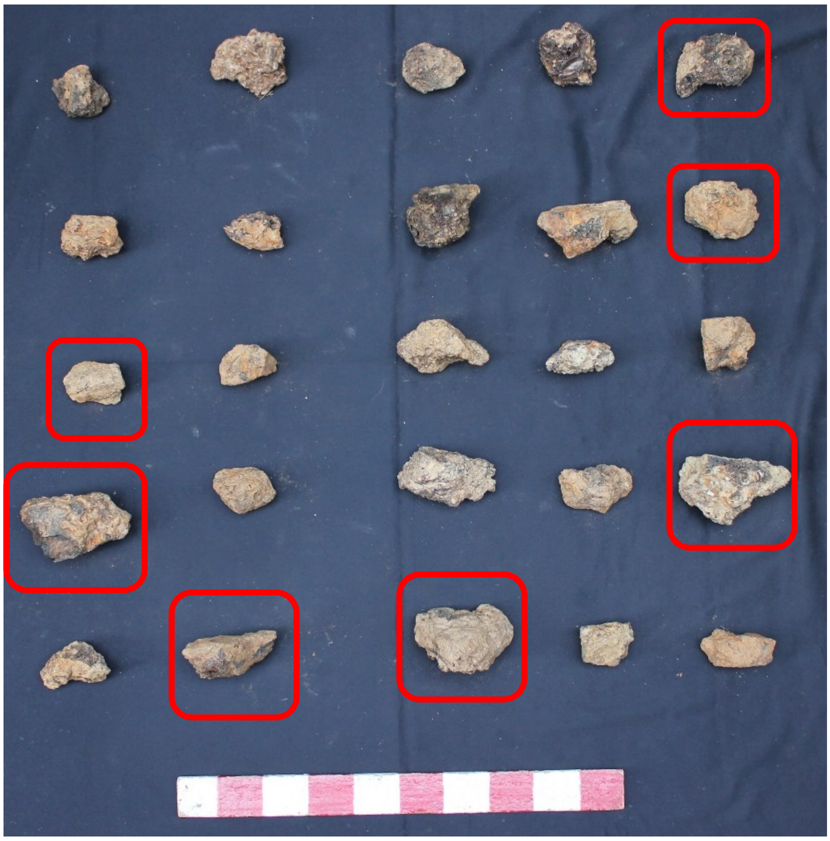
Notes: The sites highlighted in grey colour and samples in the red boxes were selected for laboratory analysis.

Ban Khok Yang, Ban Kruat subdistrict, Ban Kruat district (continued)

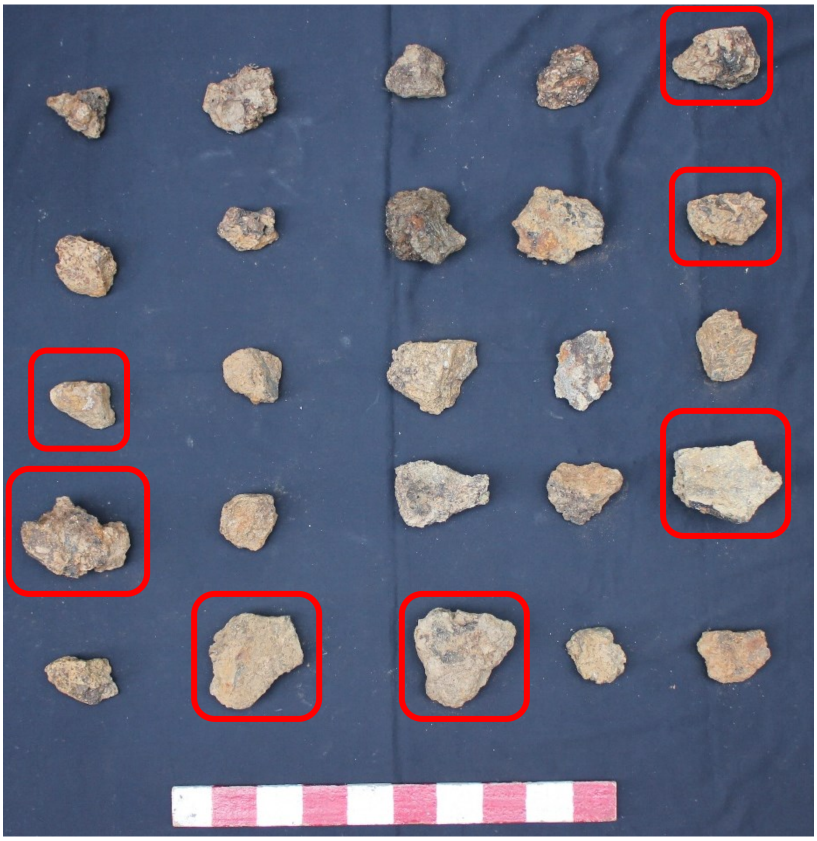
Sites	Site code in FAD1989/ FAD2008	Coordinates (Decimal degrees)	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Note
KY4	F#33	14.46181 103.10191	Small to large-sized, light to heavy, porous and dense slag	Slag 25	Slag 7	Demolished, sugar cane field, slag found distributed all over the area
KY5 Uthai Pengphet	F#34	14.45997 103.1013	Small to large-sized, light to heavy, porous and dense slag and one fragment of technical ceramic	Slag 4 Clay plug fragment 1	Clay plug fragment 1	Undisturbed mound
KY6 Chop Tirum	F#35	14.45889 103.1006	Small to large-sized, light to heavy, porous and dense slag	Slag 5	-	Mound



Slag samples collected from KY1, KY3, KY5, and KY6 (top-below)



Slag samples collected from the surface of KY4 (lateral view)



Slag samples collected from the surface of KY4 (dorsal view)

Ban Nong Chik, Panyawat subdistrict municipality, Ban Kruat district

Sites	Site code in FAD1989/ FAD2008	Coordinates (Decimal degrees)	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
NC1 Ken Junprakhon	F#27	14.43923 103.1006	Small to medium-sized, light to heavy, porous slag	Slag 5	-	Mound but partially flattened
NC2 Niwat Patarum	F#28	14.43781 103.1012	Small to large-sized, light to heavy, porous and dense slag	Slag 9	-	Demolished
NC3	F#29	14.436966 103.100444	Very few small slag	-	-	Demolished, cassava field
NC4	F#40	14.43974 103.1036	Small to large-sized, light to heavy, porous and dense slag, two large slag blocks, lumps of baked clay (technical ceramics?)	Slag 30 Slag block 1 (small fragment)	Slag 6 Slag block 1	Huge mound standing next to huge mound covered by Khmer ceramic sherds, partially flattened

Ban Nong Chik, Panyawat subdistrict municipality, Ban Kruat district (continued)

Sites	Site code in FAD1989/FAD2008	Coordinates (Decimal degrees)	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
NC5 Wat Pa Ban Kruat	-	14.43571 103.101	-	-	-	Demolished, the site is currently a temple and covered by concrete. According to the owner, slag was found here, but no slag fragments were seen during the visit.

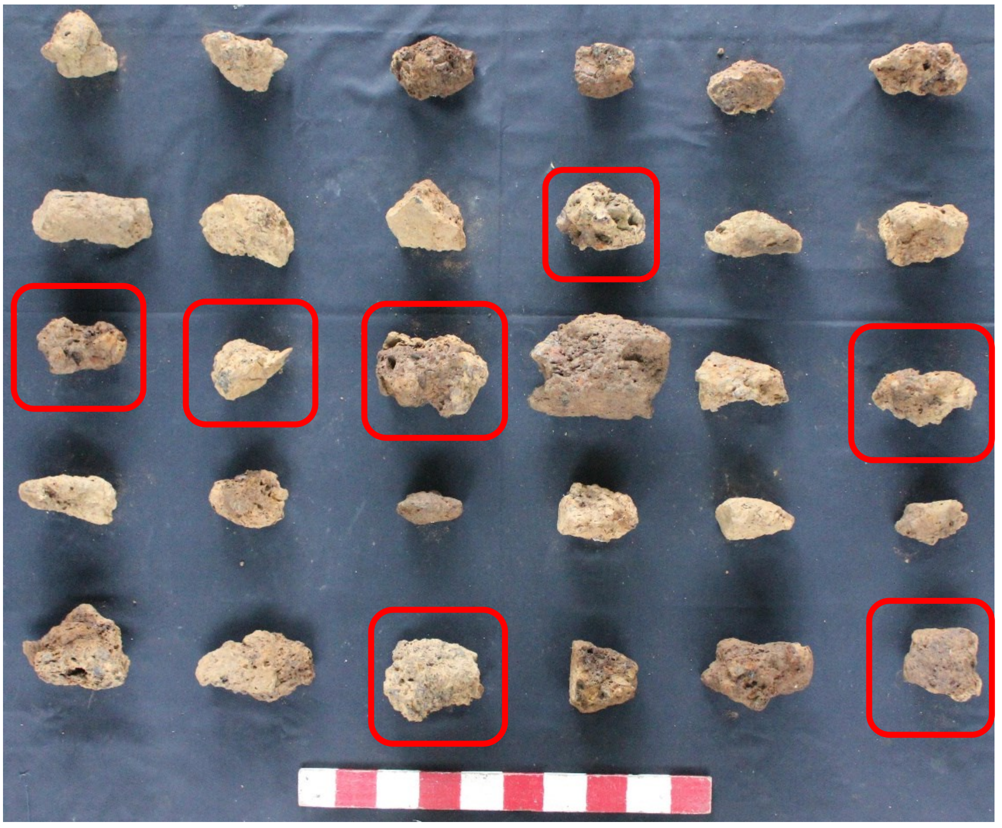
Slag collected from NC1 and NC2

Slag samples collected from the surface of NC4 (lateral view)

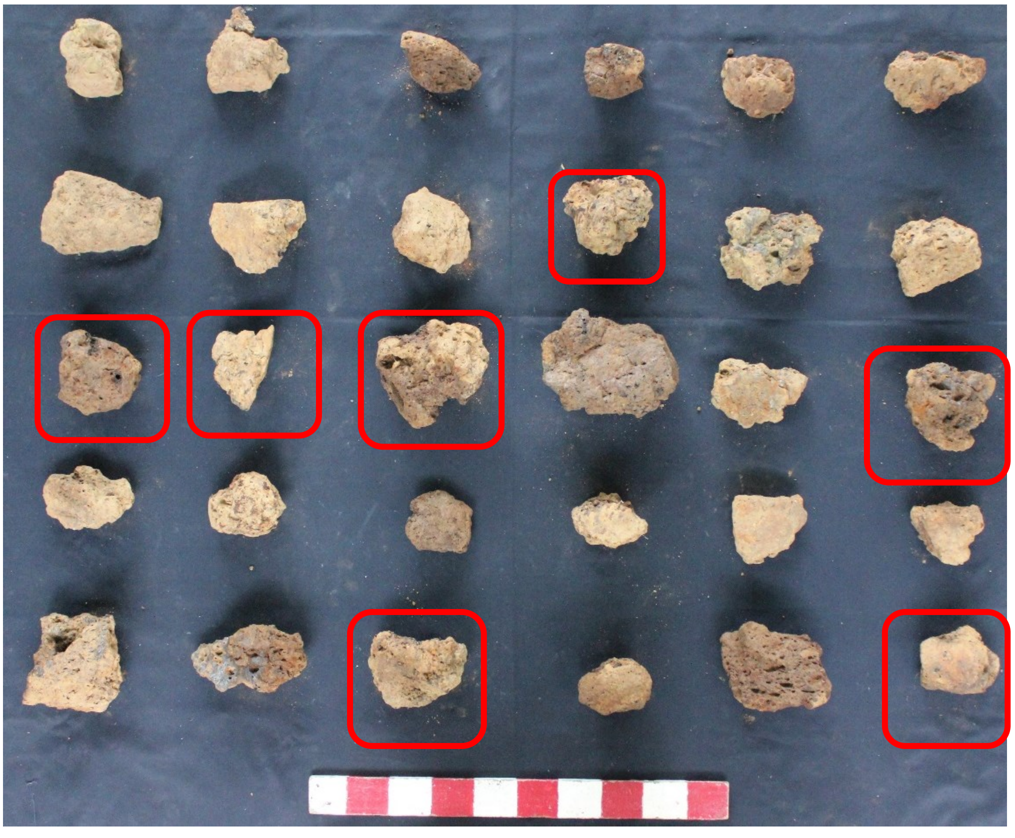
Slag samples collected from the surface of NC4 (dorsal view)

Ban Khok Sakon, Ban Kruat subdistrict, Ban Kruat district

Sites	Site code in FAD1989/FAD2008	Coordinates (Decimal degrees)	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
KSK1	F#23 (Ban Khao Din Tai)	14.44624 103.0914	Slag only be seen in the profile of this mound	Slag 30	Slag 7	Mound
KSK2	F#22 (Ban Khao Din Tai)	14.44893 103.0909	Very few small slag	-	-	Demolished, rice field
The 2012 survey could not locate this deposit.	F#21 (Ban Khao Din Tai)	14.44923 103.0903	-	-	-	Demolished, rice field



Slag samples collected from the surface of KSK1 (lateral view)



Slag samples collected from the surface of KSK1 (dorsal view)

Ban Khao Din Tai, Ban Kruat subdistrict, Ban Kruat district

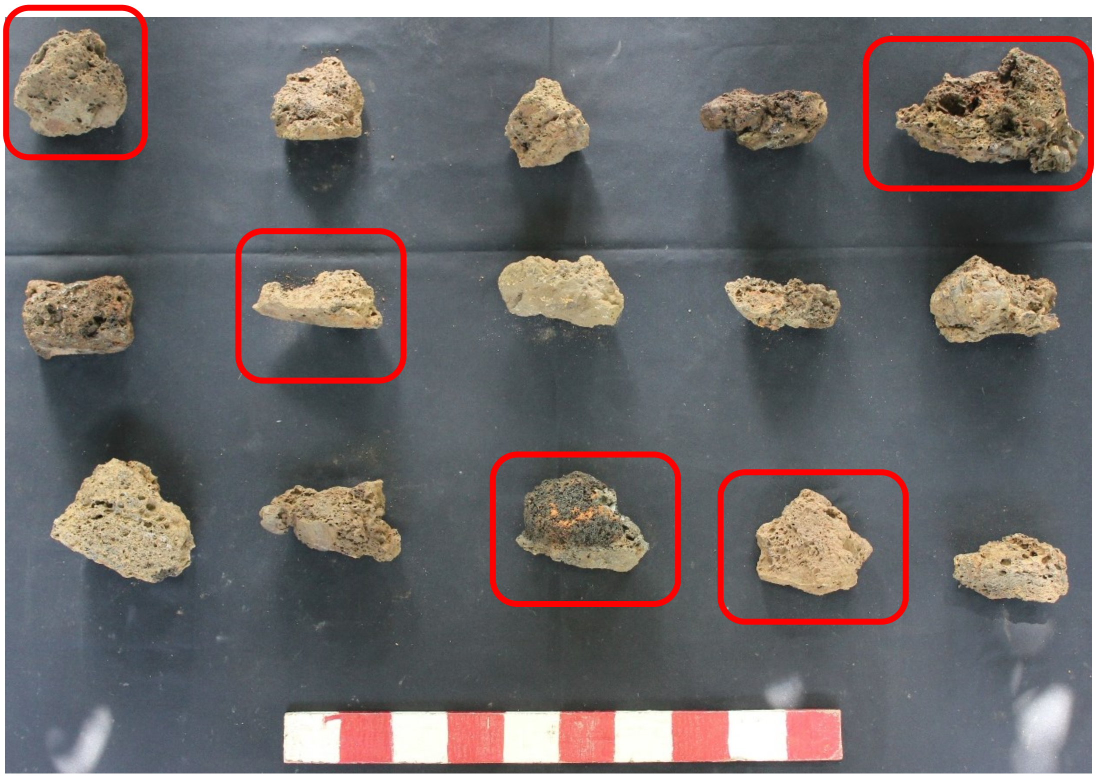
Sites	Site code in FAD1989/FAD2008	Coordinates (Decimal degrees)	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition	Notes
KDT1	F#12	14.43765 103.0808	Small to large-sized, light to heavy, porous and dense slag, technical ceramics	Slag 15	Slag 5 Furnace fragment 1	Huge mound standing next to BKDT 13, half demolished	
KDT2 (Ban Khao Din Tai site or KDT'07-08 (Lertlum *et al.* 2008))	F#13	14.437823 103.080328	Furnace remains, abundance of slag, technical ceramics, domestic pottery sherds	I visually re-examined 192 slag fragments collected by LARP archaeologists for this thesis, but, for other metallurgical finds (i.e. technical ceramics), I used the macroscopic data, mainly size and weight, recorded during the 2007-2008 excavation.	Slag 55 Clay plug fragments 2 Furnace fragments 3 Tuyère fragments 3	7 metre high and 50 metre in diameter slag mound excavated between 2007 and 2008	Metallurgical remains documented (as of 2008 excavation) Slag (estimated) 4,900m3 in test pit 1 3,040m3 in test pit 2 Furnace fragments + technical ceramic fragments 939 pieces Clay plugs 76 pieces Tuyères 331 pieces

Ban Khao Din Tai, Ban Kruat subdistrict, Ban Kruat district (continued)

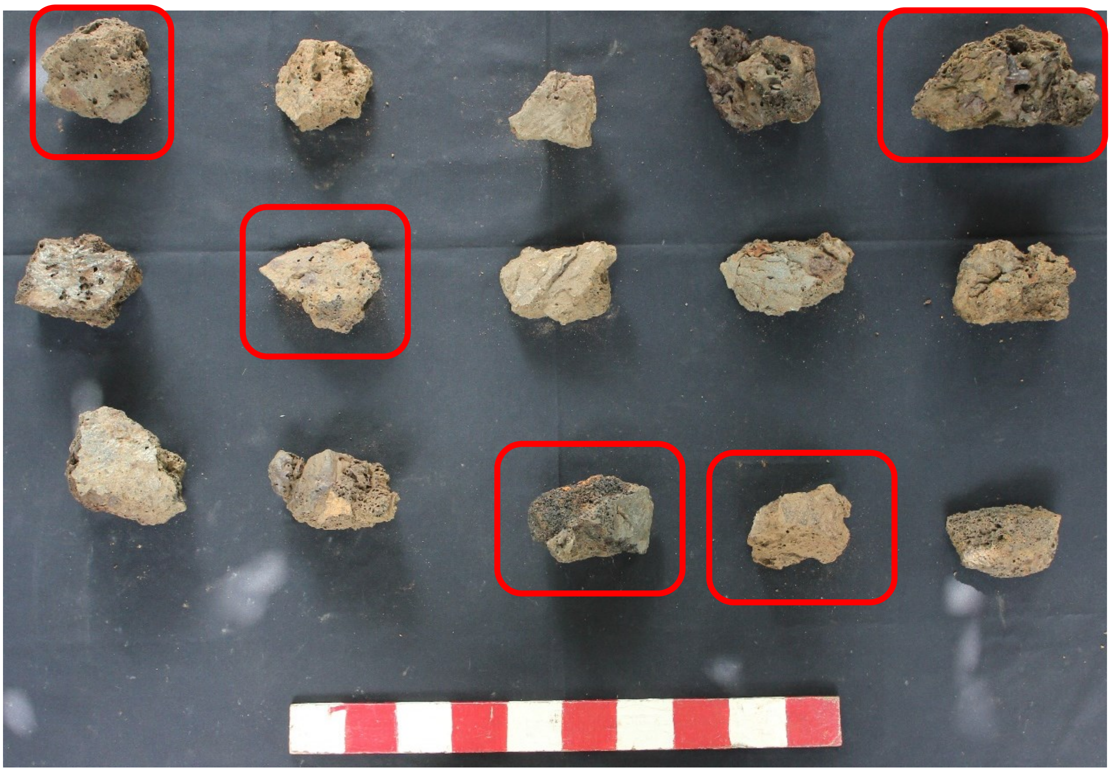
Sites	Site code in FAD1989/FAD2008	Coordinates (Decimal degrees)	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
KDT3	F#14	14.4387 103.0821	Small to large-sized, light to heavy, porous and dense slag, technical ceramics	Slag 30	Slag 5 Clay plug fragment 1 Tuyère fragment 1	Mound but flattened for growing cassava and banana
KDT4	F#15	14.4384 103.0819	Very few small slag	-	-	Mound but partially demolished for agricultural purpose
KDT5	F#16	14.4395 103.0825	Very few small slag	-	-	Mound but partially demolished for agricultural purpose

Ban Khao Din Tai, Ban Kruat subdistrict, Ban Kruat district (continued)

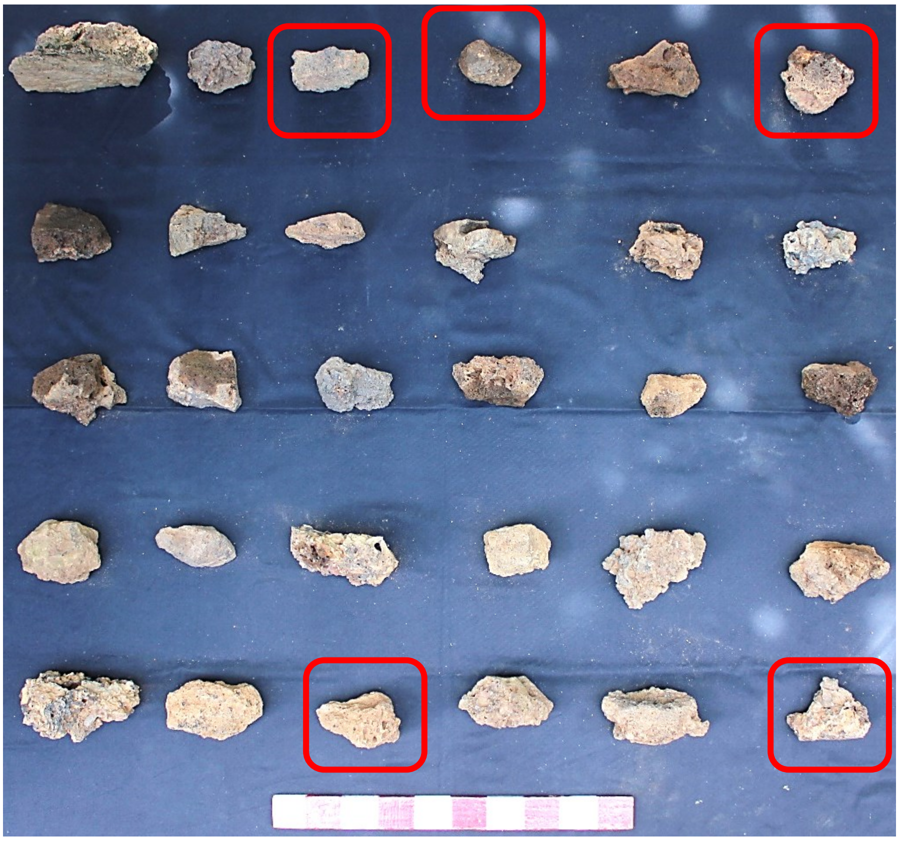
Sites	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
KDT6	F#17	14.4398 103.0825	Very few small slag	-	-	Destroyed
KDT7	F#18	14.44041 103.0825	Small to large-sized, light to heavy, porous and dense slag, technical ceramics, few earthenware and Khmer ceramic fragments	Slag 28	-	Huge mound, partially demolished with a house built on top
KDT8	F#19	14.44078 103.0823	Very few small slag	-	-	Mound but partially demolished for agricultural purpose



Slag samples collected from the surface of KDT1 (lateral view)



Slag samples collected from the surface of KDT1 (dorsal view)

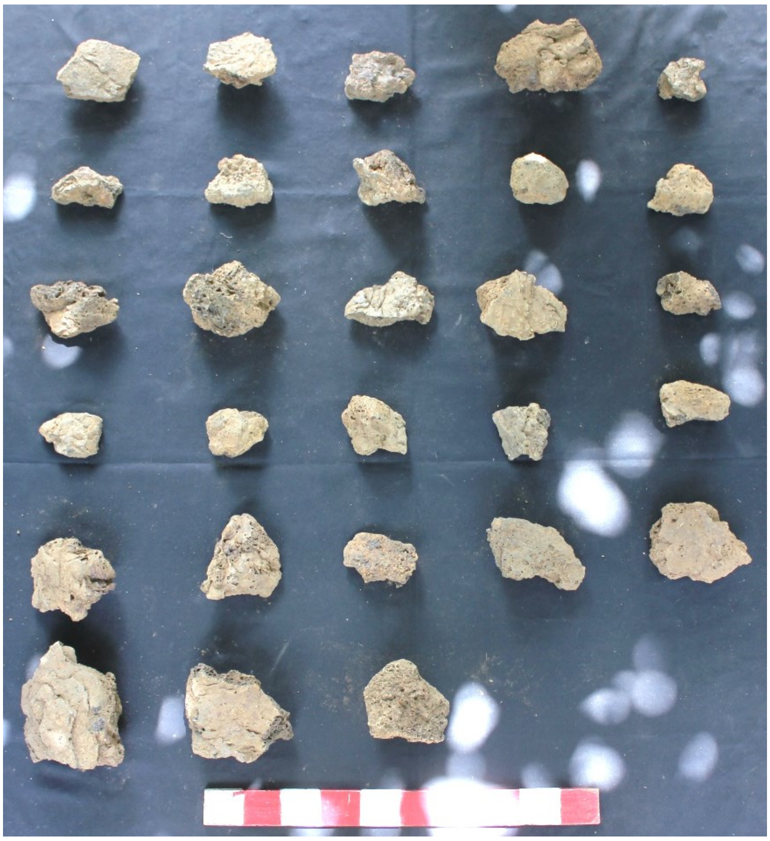


Slag samples collected from the surface of KDT3 (lateral view)

Slag samples collected from the surface of KDT3 (dorsal view)

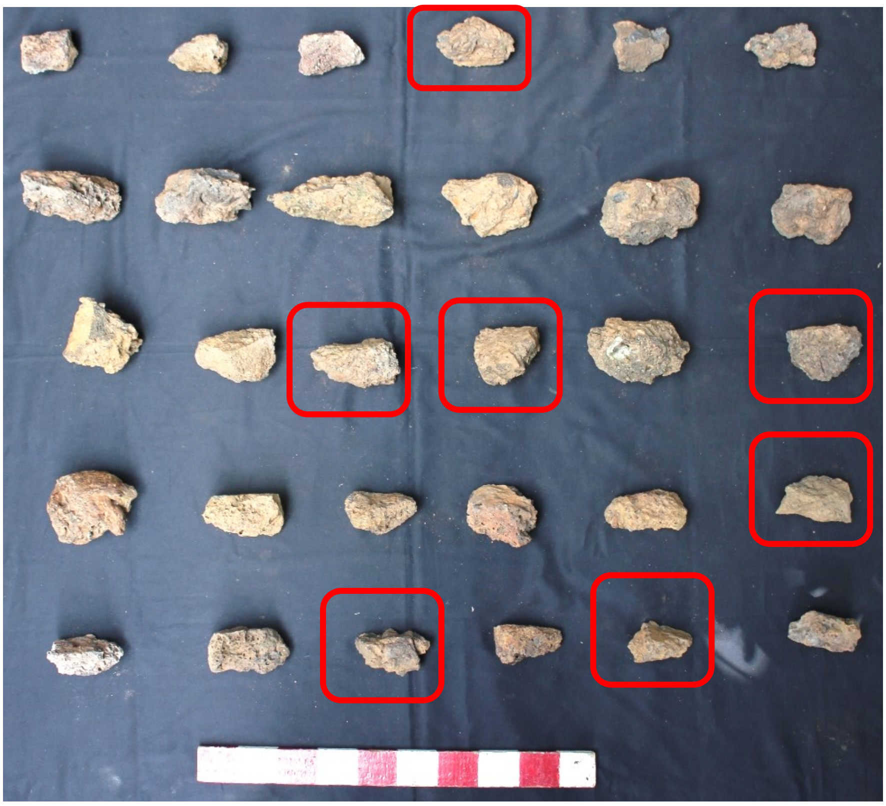
Slag samples collected from the surface of KDT8 (ventral view)

Slag samples collected from the surface of KDT8 (lateral view)


Slag samples collected from the surface of KDT8 (dorsal view)

Ban Kruat, Ban Kruat subdistrict, Ban Kruat district

Site	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
BKT5 Pataraporn Kalachewit	F#5 and 6	14.4262 103.0971	Small to large-sized, light to heavy, porous and dense slag	Slag 30	Slag 7	Undisturbed small mound situated behind the house

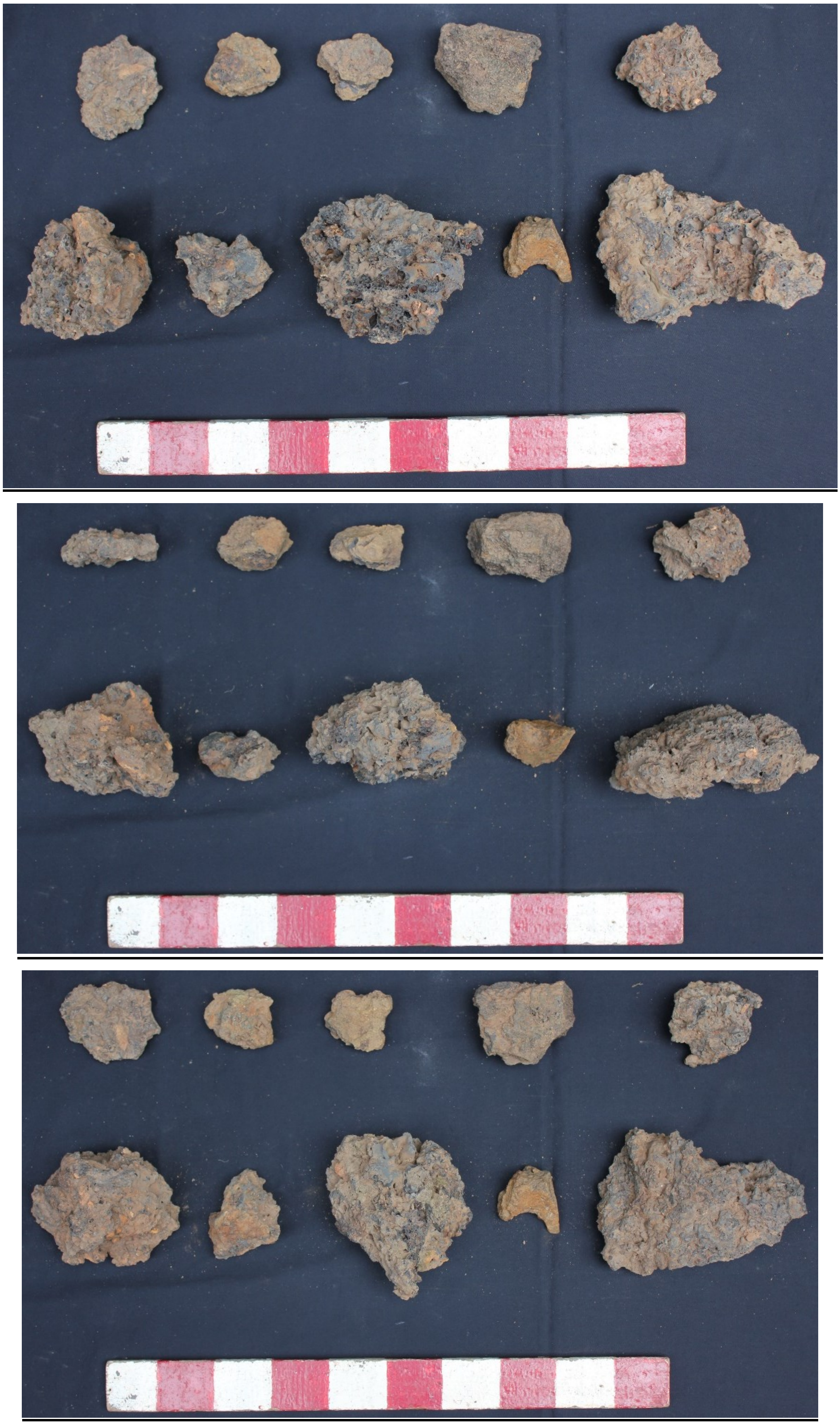


Slag samples collected from the surface of BKT5 (lateral view)

Slag samples collected from the surface of BKT5 (dorsal view)

Border Police Patrol 221 headquarters (BPP) Ban Khok Rahoei, Prasat subdistrict, Ban Kruat district

Sites	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
BPP1	(F#42?)	14.38439 103.1099	Small to large-sized, light to heavy, porous and dense slag, few probably Khmer ceramic fragments	Slag 10	-	Original form could neither be estimated nor presumed. Sugar cane field
BPP2	-	14.38356 103.1085	Very few small slag	-	-	Original form could neither be estimated nor presumed. Slag was found around the conference room



Slag samples collected from the surface of BBP1 (ventral-lateral-dorsal view)

Ban Sai Tho 8 South, Chantop Phet subdistrict, Ban Kruat district

Sites	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
STH8 M1	F#59	14.38335 103.1768	Small to large-sized, light to heavy, porous and dense slag, technical ceramics	Slag 25 Complete clay plug 1 Clay plug fragments 2 Tuyère fragments 2 Technical ceramic fragments 5	Slag 7 Clay plug fragment 1 Tuyère fragment 1	Undisturbed mound
STH8 M2 (STH7’09 Test Pit / STH8 TP1)	F#58, 60	14.38371 103.17642	Small to large-sized, light to heavy, porous and dense slag, technical ceramics, pottery fragments	Due to accident during the recording process, excavated slag was not available for this thesis	-	Excavated in 2009 (Lertlum *et al.* 2010)

Ban Sai Tho 8 South, Chantop Phet subdistrict, Ban Kruat district (continued)

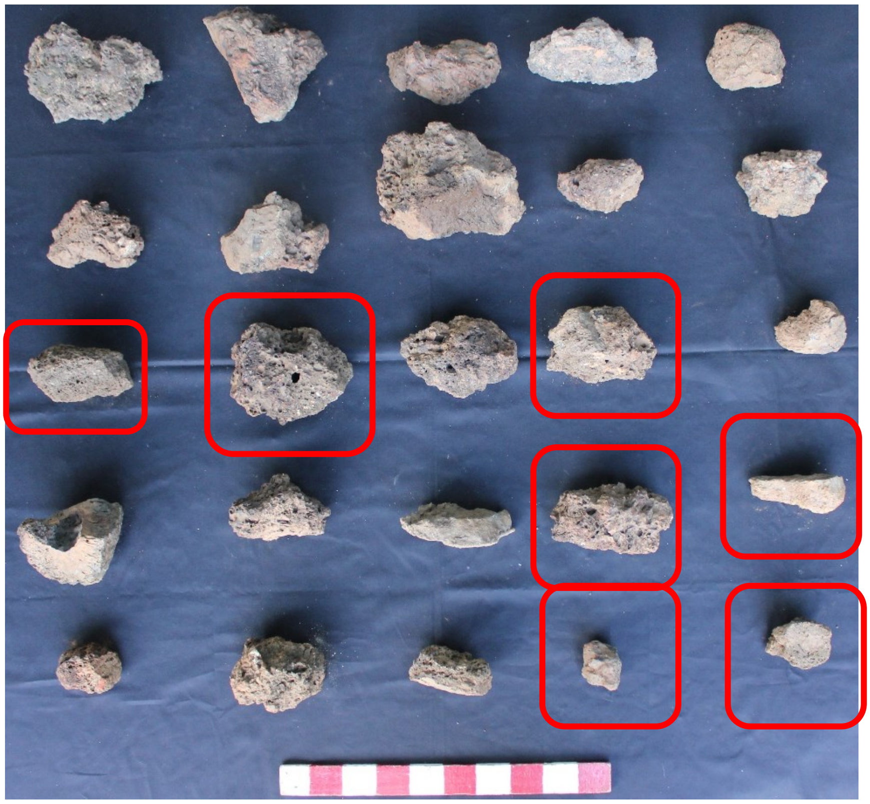
<table>
<tr><th>Sites</th><th>Site code in FAD1989/FAD2008</th><th>Decimal degrees</th><th>Evidence found</th><th>Samples collected for preliminary analysis</th><th>Samples collected for laboratory-based analyses</th><th>Current condition</th></tr>
<tr><td>STH8 M3</td><td>F#57</td><td>14.38446
103.17599</td><td>Small to large-sized, light to heavy, porous and dense slag, technical ceramics, slag blocks</td><td>Slag 16
Clay plug fragments 2
Tuyère fragment 1
Technical ceramic fragments 4</td><td>-</td><td rowspan="2">Undisturbed mound, Two joining slag mounds</td></tr>
<tr><td>STH8 M4</td><td>F#56</td><td>14.38445
103.17557</td><td>Small to large-sized, light to heavy, porous and dense slag, technical ceramics, slag blocks</td><td>Slag 20
Tuyère fragment 1
Technical ceramic fragments 5</td><td>-</td></tr>
<tr><td>STH8 M5</td><td>F#67</td><td>14.38441
103.17475</td><td>Few small to medium-sized slag</td><td>-</td><td>-</td><td>Undisturbed mound</td></tr>
</table>

Ban Sai Tho 8 South, Chantop Phet subdistrict, Ban Kruat district (continued)

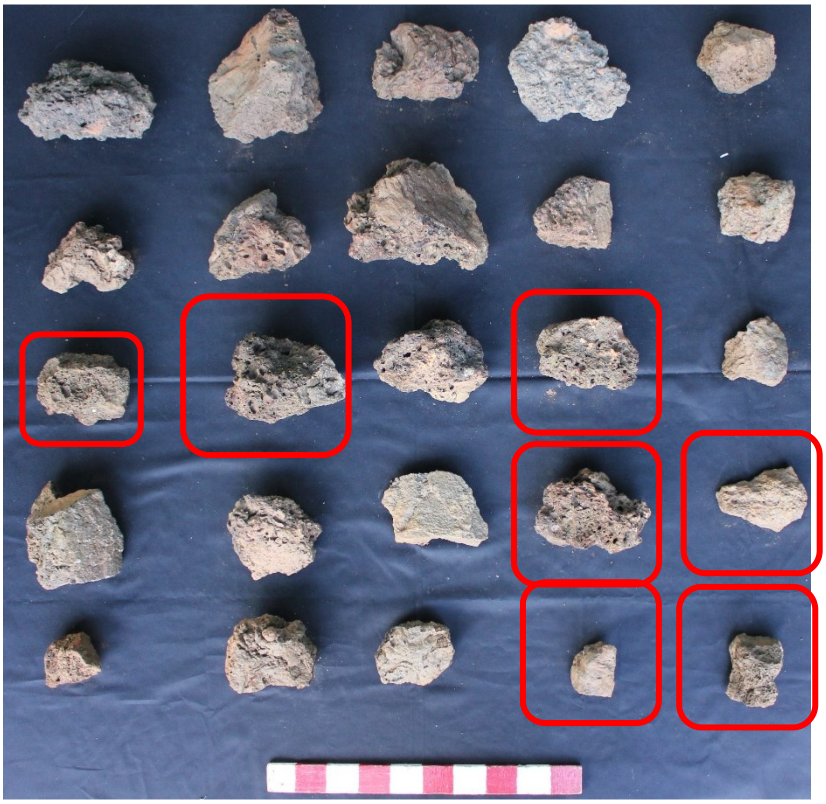
Sites	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
STH8 M6	-	14.384 103.17456	Slag	-	-	Undisturbed mound
STH8 M7	F#66	14.38389 103.17435	Slag	-	-	Undisturbed mound
STH8 M8	F#65	14.38316 103.17464	Small to large-sized, light to heavy, porous and dense slag, technical ceramics, slag blocks	-	-	Undisturbed mound
STH8 M9	F#64	14.3825 103.17558	Small to large-sized, light to heavy, porous and dense slag, technical ceramics	-	-	Undisturbed mound
STH8 M10	F#63	14.92831 103.17614	Small to large-sized, light to heavy, porous and dense slag, technical ceramics	-	-	Undisturbed mound

Ban Sai Tho 8 South, Chantop Phet subdistrict, Ban Kruat district (continued)

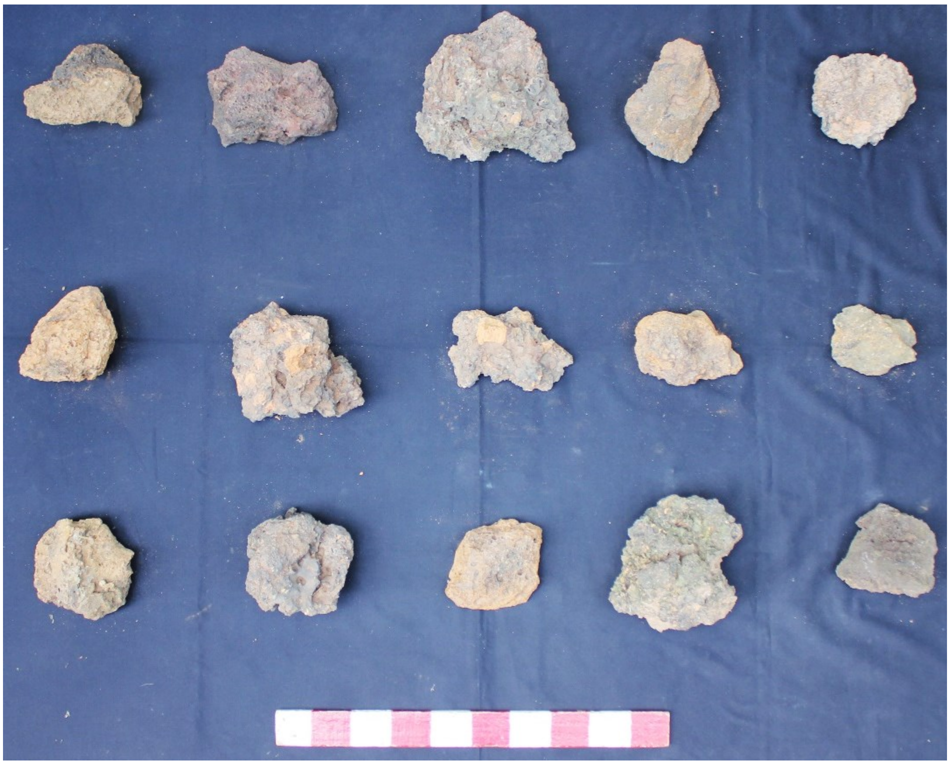
Sites	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
STH8 M11	F#62	14.38265 103.17652	Small to large-sized, light to heavy, porous and dense slag, technical ceramics and, according to the owner, complete Khmer vessel and bronze ornaments were found.	-	-	Undisturbed mound



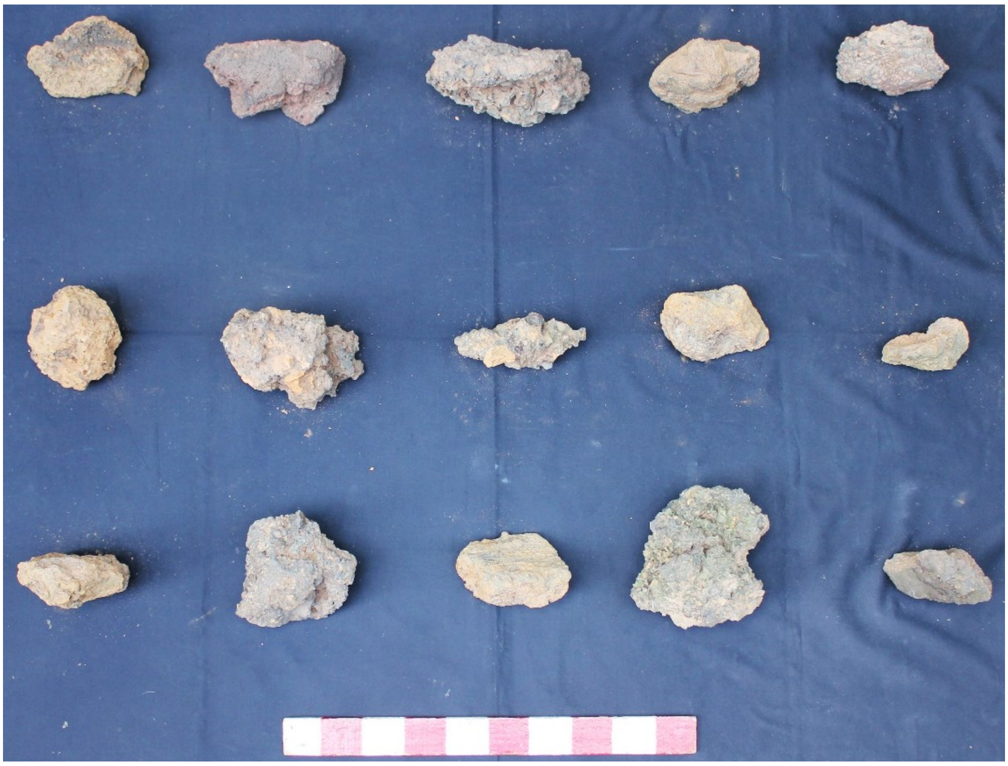
Slag samples collected from the surface of STH8 M1 (lateral view)



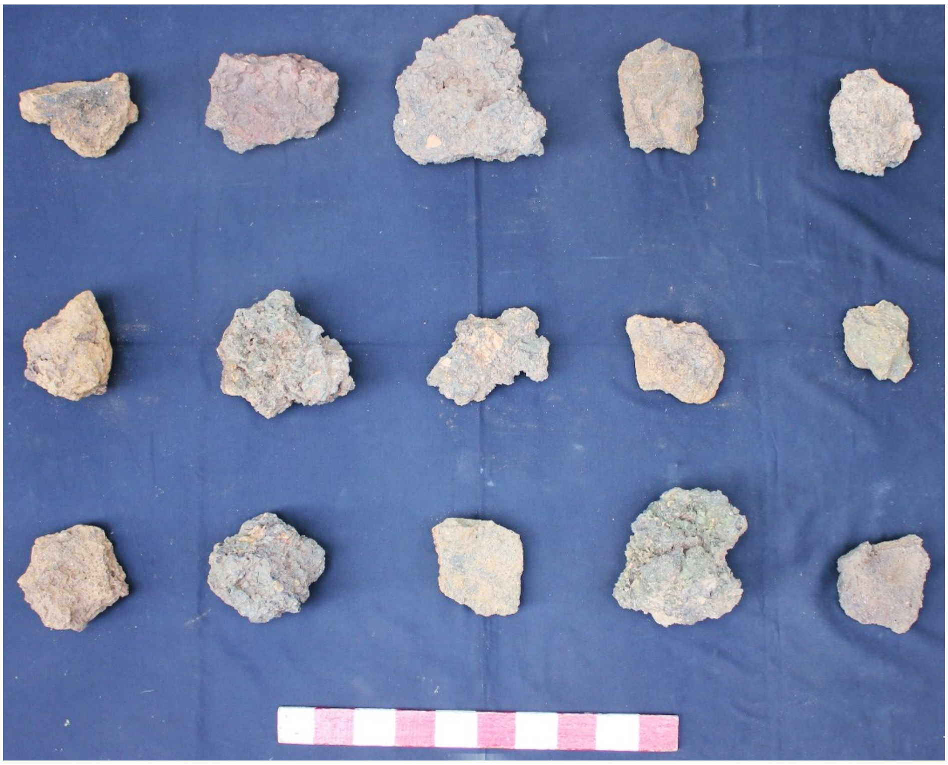
Slag samples collected from the surface of STH8 M1 (dorsal view)



Slag samples collected from the surface of STH8 M3 (ventral view)



Slag samples collected from the surface of STH8 M3 (lateral view)



Slag samples collected from the surface of STH8 M3 (dorsal view)

Slag samples collected from the surface of STH8 M4 (ventral view)

Slag samples collected from the surface of STH8 M4 (lateral view)

Slag samples collected from the surface of STH8 M4 (dorsal view)

Ban Sai Tho 8 South 2, Chantop Phet subdistrict, Ban Kruat district

Sites	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
STH8/2 M1	F#52	14.37962 103.1802	Small to large-sized, light to heavy, porous and dense slag, technical ceramics	Slag 10 Technical ceramic fragment 1	-	Original size of mound cannot be estimated as it is bulldozed
STH8/2 M2	F#51	14.37977 103.1804	Small to large-sized, light to heavy, porous and dense slag, technical ceramics	Slag 10 Technical ceramic fragments 3	-	Mound 2 and 3 are connected but original size of mound cannot be estimated as it is bulldozed
STH8/2 M3	F#53	14.37898 103.1806	Small to large-sized, light to heavy, porous and dense slag, technical ceramics, two large slag blocks	Slag 30 Technical ceramic fragments 5	-	

Ban Sai Tho 8 South 2, Chantop Phet subdistrict, Ban Kruat district (continued)

Sites	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
STH8/2 M4	F#54	14.3791 103.1811	Small to large-sized, light to heavy, porous and dense slag, technical ceramics, a large slag block	A fragment of slag block 1	A fragment of slag block 1	Original size of mound cannot be estimated as it is bulldozed
STH8/2 M5	F#49	14.38037 103.1816	Small to large-sized, light to heavy, porous and dense slag	-	-	Original size of mound cannot be estimated as it is bulldozed
STH8/2 M6	F#50	14.38025 103.181	Small to large-sized, light to heavy, porous and dense slag, technical ceramics	Slag 30 Technical ceramic fragment 1	Slag 7 Technical ceramic fragment 1	Undisturbed mound

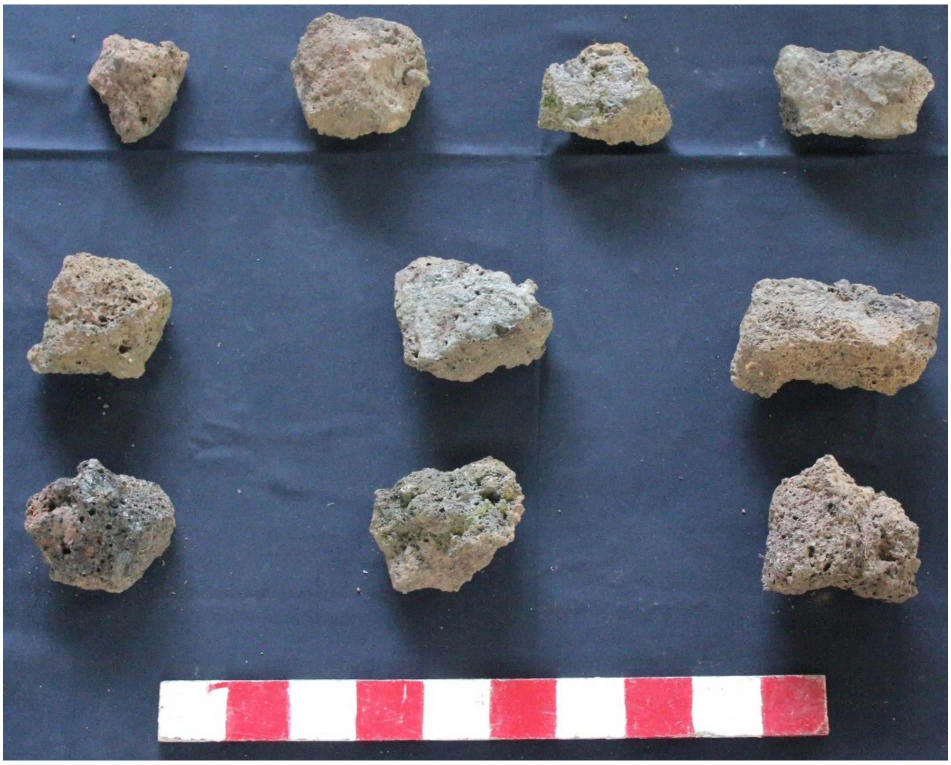
Slag samples collected from the surface of STH8/2 M1 (ventral view)

Slag samples collected from the surface of STH8/2 M1 (lateral view)

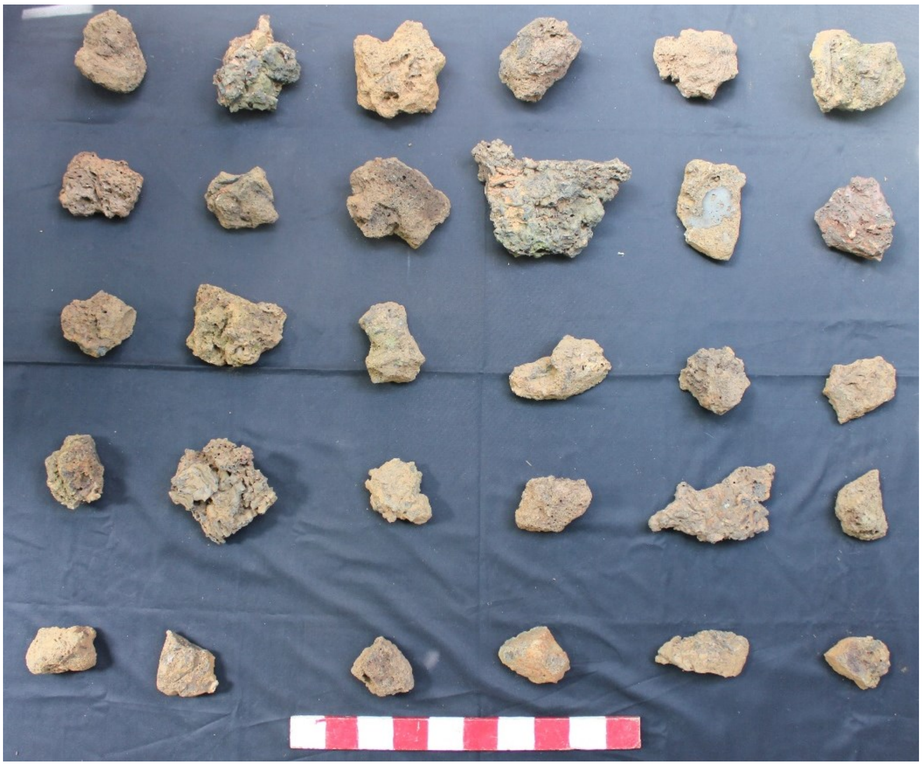
Slag samples collected from the surface of STH8/2 M1 (dorsal view)

Slag samples collected from the surface of STH8/2 M2 (ventral view)

Slag samples collected from the surface of STH8/2 M2 (lateral view)

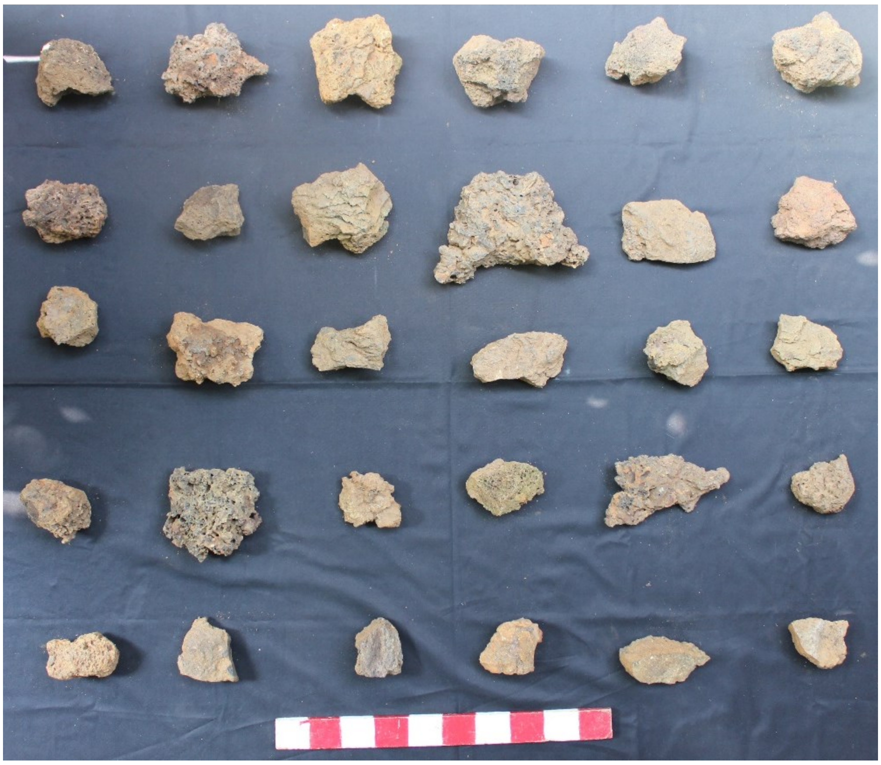


Slag samples collected from the surface of STH8/2 M2 (dorsal view)

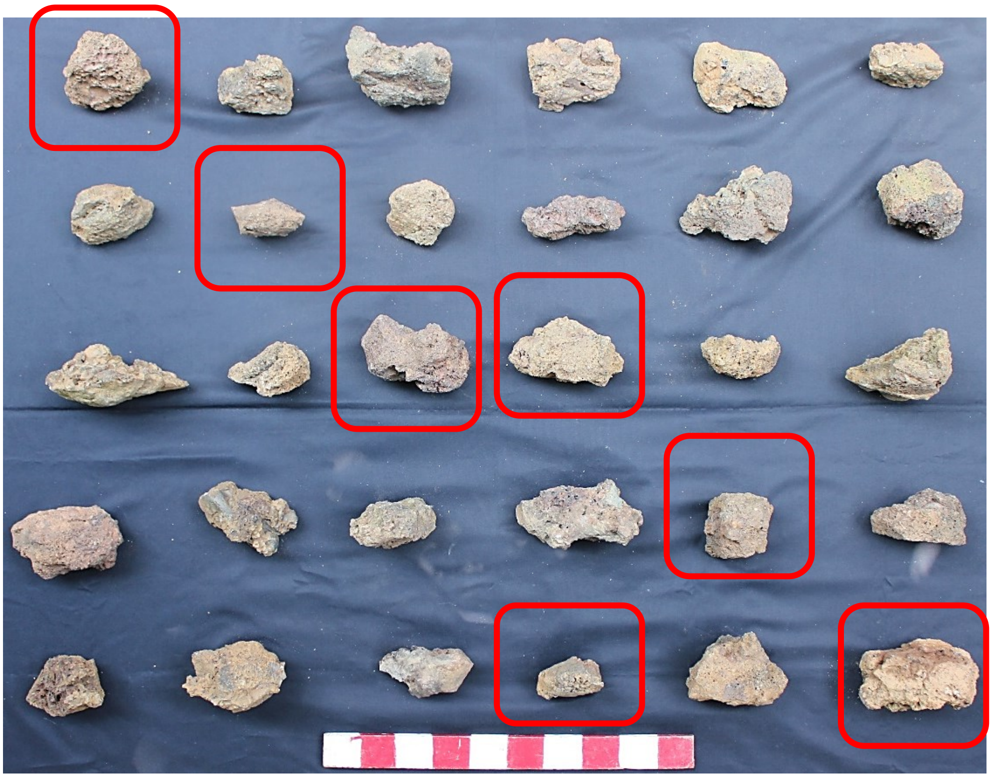


Slag samples collected from the surface of STH8/2 M3 (ventral view)

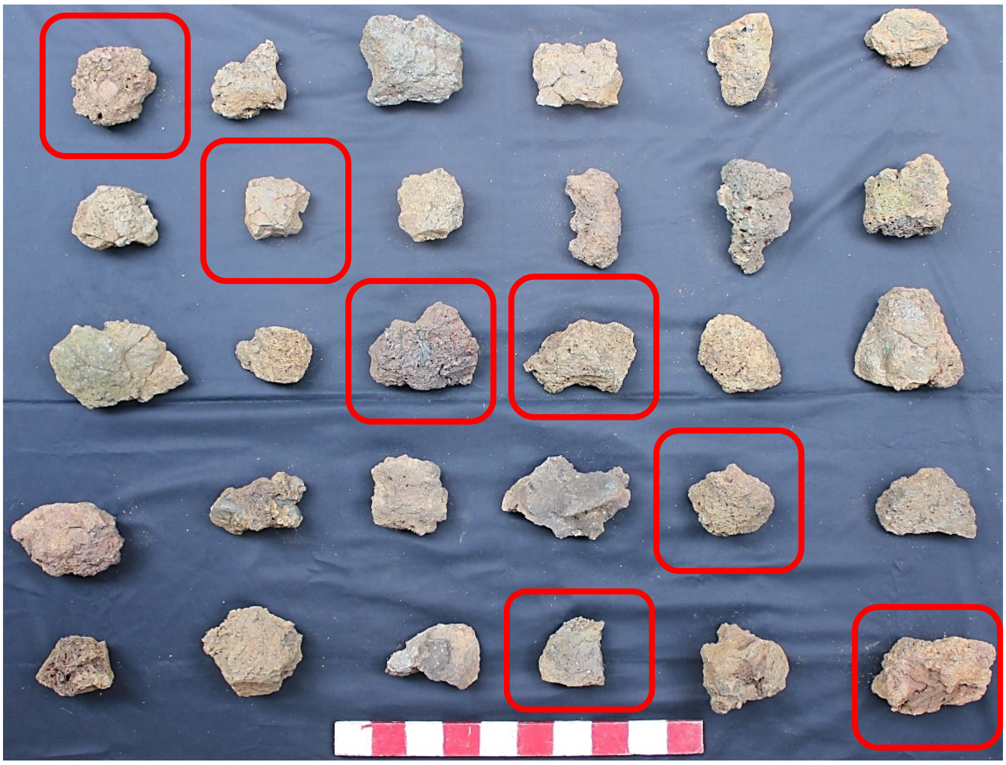
Slag samples collected from the surface of STH8/2 M3 (lateral view)



Slag samples collected from the surface of STH8/2 M3 (dorsal view)



Slag samples collected from the surface of STH8/2 M6 (lateral view)



Slag samples collected from the surface of STH8/2 M6 (dorsal view)

Ban Sai Tho 10 North, Sai Taku subdistrict, Ban Kruat district

Sites	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
STH10 South	This 2012 survey could not match the coordinates reported by the previous FAD surveys.	14.41243 103.2012	Dense distribution of small to large-sized, light to heavy, porous and dense slag, technical ceramics	Slag 30 Complete clay plug 1 Clay plug fragment 3	Slag 7 Clay plug fragment 1	The area was completely flattened during 1977-1980 but slag can be seen across this area. The site is currently a rubber tree farm.
STH10 B (STH10 East)		14.41322 103.2025	Dense distribution of small to large-sized, light to heavy, porous and dense slag, technical ceramics	Slag 30 Technical ceramic fragments 3	-	

Ban Sai Tho 10 North, Sai Taku subdistrict, Ban Kruat district (continued)

<table>
<tr><th>Sites</th><th>Site code in FAD1989/FAD2008</th><th>Decimal degrees</th><th>Evidence found</th><th>Samples collected for preliminary analysis</th><th>Samples collected for laboratory-based analyses</th><th>Current condition</th></tr>
<tr><td>STH10 C

(STH10 Central 1)</td><td rowspan="2">This 2012 survey could not match the coordinates reported by the previous FAD surveys.</td><td>14.41303

103.2019</td><td>Very few Medium to large-sized dense slag</td><td>-</td><td>-</td><td rowspan="2">The area was completely flattened during 1977-1980 but slag can be seen across this area.

The site is currently a rubber tree farm.</td></tr>
<tr><td>STH10 D

(STH10 Central 2)</td><td>14.41348

103.2018</td><td>Very few Medium to large-sized dense slag</td><td>Slag 5</td><td>-</td></tr>
</table>

Ban Sai Tho 10 North, Sai Taku subdistrict, Ban Kruat district (continued)

Sites	Site code in FAD1989/FAD2008	Decimal degrees	Evidence found	Samples collected for preliminary analysis	Samples collected for laboratory-based analyses	Current condition
STH10 E (STH10 Central 3)	This 2012 survey could not match the coordinates reported by the previous FAD surveys.	14.41368 103.2017	Very few Medium to large-sized dense slag	-	-	The area was completely flattened during 1977-1980 but slag can be seen across this area. The site is currently a rubber tree farm.
STH10 F (STH10 West)		14.41398 103.2008	Small porous slag	-	-	

Slag samples collected from the surface of STH10 S (lateral view)

Slag samples collected from the surface of STH10 S (dorsal view)

Slag samples collected from the surface of STH10 B (ventral view)

Slag samples collected from the surface of STH10 B (lateral view)

Slag samples collected from the surface of STH10 B (dorsal view)

Appendix D Summary of metallurgical finds examined in this research

Cluster	Site	Samples collected for the preliminary visual comparison					Samples collected for laboratory-based analyses						
		slag	tuyères	clay plugs	furnace fragments	unidentified	slag	tuyères	clay plugs	furnace fragments	unidentified	Ceramic fragments	Others
Khok Yang	KY1	5	-	1	-	-	-	-	1	-	-	-	-
	KY3	5	-	-	-	-	-	-	-	-	-	-	-
	KY4	25	-	-	-	-	7	-	-	-	-	-	-
	KY5	4	-	-	-	-	-	-	-	-	-	-	-
	KY6	5	-	-	-	-	-	-	-	-	-	-	-
	KY kiln	-	-	-	-	-	-	-	-	-	-	-	-
Nong Chik	NC1	5	-	-	-	-	-	-	-	-	-	-	-
	NC2	9	-	-	-	-	-	-	-	-	-	-	-
	NC4	30	-	-	-	4	7	-	-	-	-	1	-
Khok Sakon	KSK1	30	-	-	-	-	7	-	-	-	-	-	-

Cluster	Site	Samples collected for preliminary examination					Samples collected for laboratory-based analyses							
		slag	tuyères	clay plugs	furnace fragments	unidentified	slag	tuyères	clay plugs	furnace fragments	unidentified	Ceramic fragments	Others
Khao Din Tai	KDT1	15	1	-	-	3	5	-	-	1	-	-	Archaeological laterite fragments 2
	KDT2	192	-	-	-	-	55	3	2	3	-	2	-
	KDT3	30	1	2	-	2	5	1	1	-	-	-	-
	KDT7	28	-	-	-	-	-	-	-	-	-	-	-
	Huai Tasek	-	-	-	-	-	-	-	-	-	-	-	Clay samples 2
Ban Kruat	BKT5	30	-	-	-	-	7	-	-	-	-	-	-
Khok Rahoei	BPP	10	-	-	-	-	-	-	-	-	-	-	Geological laterite 1
Bai Sai Tho8	STH8 M1	25	2	3	5	-	7	-	1	1	-	-	-
	STH8 M3	15	1	2	4	5	-	-	-	-	-	-	-
	STH8 M4	20	1	-	-	-	-	-	-	-	-	-	-
	STH8 Trench 1	76	-	-	-	-	7	1	-	1 (Hearth)	-	2	Archaeological laterite nodules 6
	STH8 Trench 2		-	-	-	-	5	-	-	-	-	-	-
	STH8 Test Pit 1	-	-	-	-	-	-	-	1	1	-	-	-
	Huai Tako	-	-	-	-	-	-	-	-	-	-	-	Clay 1

Cluster	Site	Samples collected for preliminary examination					Samples collected for laboratory-based analyses						
		slag	tuyères	clay plugs	furnace fragments	unidentified	slag	tuyères	clay plugs	furnace fragments	unidentified	Ceramic fragments	Others
Ban Sai Tho8/2	STH8/2 M1	10	-	-	-	1	-	-	-	-	-	-	-
	STH8/2 M2	10	-	-	-	2	-	-	-	-	-	-	-
	STH8/2 M3	30	-	-	-	5	-	-	-	-	-	-	-
	STH8/2 M4	1	-	-	-	-	1	-	-	-	-	-	-
	STH8/2 M6	30	-	-	-	1	7	-	-	-	1	-	-
Ban Sai Tho10	STH10 S	30	-	4	1	3	7	-	1	-	-	-	-
	STH10 B	30	-	-	-	-	-	-	-	-	-	-	-
	STH10 D	5	-	-	-	-	-	-	-	-	-	-	-
Sum		705	6	12	10	26	127	5	7	6	1	5	

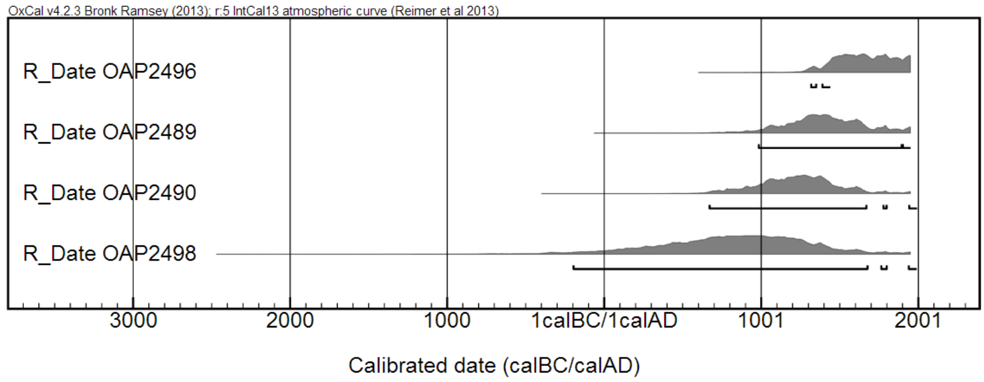
Appendix E Previous dating programmes for the archaeological site of KDT2 and STH8 T1

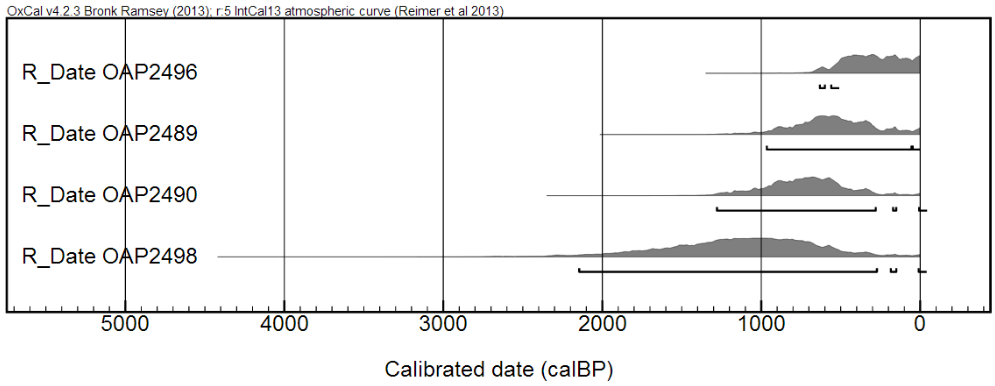
The first attempt: radiometric dating

A series of efforts to date the metallurgical sites began as soon as the first season of the excavations at KDT 2 finished in 2007. Four charcoal samples found in association with the smelting activity were subjected to radiometric dating to the Thailand Institute of Nuclear Technology in Bangkok. Unfortunately, either the technique or the samples failed to give a reliable result as they returned an exceptionally wide range of dates after being calibrated with OXCAL 4.2 (Ramsey 2013) using curve IntCal13 (Reimer *et al.* 2013). The dates obtained spanned from 196calBC to undeterminable dates (Thailand Institute of Nuclear Technology 2007) or from the late Iron Age (200BC–AD500) to the Ayutthayan period (13th-18th century AD) in the Thai chronological framework. Interestingly, the date suggested that the furnaces 1 and 2 could be contemporaneous; although, the dating result indeed suffered from the large error margins. The dates were therefore not used by the author, regardless of them being used as the preliminary dates of the site by LARP (Lertlum *et al*. 2008, 182; Yoopom 2010).

Lab no.	Sample	Context	Date (BP)	Calibrated date range (calBC/AD) (95.4% probability)	Calibrated date range (calBP) (95.4% probability)
OAP 2496	Charcoal	In the excavated layer of S – 80 cm.dt.	260±210	AD1319-1351 (2.0%) AD1391-… (93.4%)	631-600 (2.0%) 560-… (93.4%)
OAP 2489	Charcoal	Inside furnace#1	560±260	AD985-1896 (92.9%) AD1903-… (2.5%)	965-55 (92.9%) 48-… (2.5%)
OAP 2490	Charcoal	Inside furnace#2	730±270	AD671-1670 (94.7%) AD1779-1799 (0.5%) AD1943-… (0.2%)	1279-280 (94.7%) 171-151 (0.5%) 7-… (0.2%)
OAP 2498	Charcoal	Collected from a slag found in an excavated layer of 165 cm.dt.	1,100±470	196BC-AD1678 (94.9%) AD1765-1800 (0.4%) AD1940-… (0.2%)	2145-273 (94.9%) 185-150 (0.4%) 10-… (0.2%)

Radiocarbon dating results of the charcoals collected at KDT 2. Calibration was done with Oxcal 4.2 (Ramsey 2013) using curve IntCal13 (Reimer et al. 2013)





Probability distributions of calibrated radiocarbon dates of KDT 2 (calBC/calAD (above) and calBP (below))

The second attempt: thermoluminescene dating

Following the unexpected problems with radiocarbon dates, the regenerative thermoluminescence dating technique was employed in an attempt to rectify this problem. By this time, excavation of the second site, Ban Sai Tho7, was just finished, so it was included in this ongoing dating programme. Technical ceramics were collected from different excavation levels for this task, hoping that this determination was would deliver direct dates for debris in direct association to the smelting operation. The results seemed initially more convincing because they appeared more precise consistent among them than the large chronological ranges offered by radiocarbon. KDT 2 was consequently dated to 1,111–1,133 BP, and Ban Sai Tho7 1,179–1,202 BP (Won-in 2011). These dates, approximately 9th-10th century AD, were deemed of great interest for the local archaeology, as they suggested that much of the production evidence could date to the transition period into the Angkorian period, which took place approximately in the 10th century AD. The dates obtained also helpfully bridged the late Iron Age and Angkorian occupations recorded archaeologically in the local area. On the basis of these dates, it was thought that the material remains would allow an examination of the role of iron production in the context of early Imperial Angkorian political economy.

Even though these dates seemed more reliable and consistent with archaeological expectations, the sample preparation and results had to be brought into question. The most notable issue was the differences in the quantification of K_2O in the technical ceramics when comparing those of the TL lab with the results obtained in the course of the current research. Both microprobe and XRF revealed detectable levels of K_2O in all the technical ceramic samples selected for this research (approx. 0.1-1 wt% depending on the sample and instrument); moreover, the analysis showed that the technical ceramics in Ban Kruat were likely to be less chemical heterogeneous. Conversely, the measurements performed in the course of TL dating could not detect this compound. This raised a great concern for the reliability of the dates provided.

Lab no.	Sample	Context	K_2O (%)	U (ppm)	Th (ppm)	W.C. (%)	AD (mGy/a)	PD (Gy)	TL age (BP)	Age error (BP)
A_0335	Probable furnace wall fragment	KDT'07 TP.1 NEQ S-100 cm.dt.	Nil	0.167	8.568	2.564	0.782	0.886	1,133	168
A_0336	Probable furnace wall fragment	KDT'07 TP.1 SWQ L.11 170-180 cm.dt.	Nil	0.256	7.948	0.935	0.757	0.860	1,135	76
A_0337	Probable furnace wall fragment	KDT'07 TP.1 L.12 – 17	Nil	0.311	6.801	2.830	0.685	0.761	1,111	192

Thermoluminescene dates of KDT 2 (Won-in 2011)

Lab no.	Sample	Context	K_2O (%)	U (ppm)	Th (ppm)	W.C. (%)	AD (mGy/a)	PD (Gy)	TL age (BP)	Age error (BP)
A_0338	Tuyère fragment	STH'09 L1 60-70 cm.dt.	Nil	Nil	9.046	2.994	0.777	0.916	1,179	71
A_0339	Tuyère fragment	STH'09 L3 80-90 cm.dt.	Nil	Nil	7.878	2.536	0.690	0.819	1,186	142
A_0340	Probable furnace wall fragment	STH'09 L4 90-100 cm.dt.	Nil	4.509	7.243	1.480	1.740	2.045	1,176	202
A_0341	Probable furnace wall fragment	STH'09 L4 90-100 cm.dt.	Nil	Nil	6.530	0.370	0.589	0.708	1,202	180

Thermoluminescence dates of Ban Sai Tho7 (Won-in 2011)

Appendix F Data summary of slag collected for preliminary visual examination

Cluster	Site		Weight (g)	Size (cm)		
				Length	Width	Thick
Khok Yang	KY1	mean	91	6.6	5.6	4.5
	n=5	SD	19	1.2	1.4	0.4
		CV	21	18	25	10
	KY3	mean	492	11.0	9.2	6.8
	n=5	SD	220	2.4	2.0	0.8
		CV	45	21	22	12
	KY4	mean	231	9.2	7.2	5.7
	n=25	SD	137	1.9	1.6	1.1
		CV	60	20	22	20
	KY5	mean	231	9.2	6.6	5.5
	n=4	SD	26	0.7	0.9	0.8
		CV	11	8	13	15
	KY6	mean	310	9.3	7.6	5.7
	n=5	SD	131	2.4	1.2	1.2
		CV	42	26	15	21
Nong Chik	NC1	mean	235	7.0	9.0	5.9
	n=5	SD	72	1.1	1.0	1.1
		CV	31	16	11	18
	NC2	mean	261	9.7	6.6	5.0
	n=5	SD	101	1.3	1.0	1.1
		CV	39	13	14	23
	NC4	mean	418	11.3	9.0	7.0
	n=30	SD	196	2.4	1.6	2.1
		CV	47	21	18	29
Khok Sakon	KSK1	mean	418	11.2	9.2	7.2
	n=30	SD	280	2.0	1.4	1.6
		CV	67	18	15	23

Cluster	Site		Weight (g)	Size (cm)		
				Length	Width	Thick
Khao Din Tai	KDT1	mean	352	11.5	8.6	6.8
	n=15	SD	112	2.2	1.1	1.2
		CV	32	19	13	18
	KDT2	mean	122	7.7	5.6	3.3
	n=189	SD	125	2.4	1.9	1.6
		CV	103	30	34	47
	KDT2 F7	mean	806	14.6	10.9	11.2
	n=6	SD	411	1.9	2.6	13.6
		CV	51	13	24	122
	KDT3	mean	556	12.5	9.9	6.9
	n=30	SD	281	2.6	2.4	1.4
		CV	50	21	24	20
	KDT7	mean	353	10.8	8.0	5.9
	n=28	SD	268	2.4	2.0	1.8
		CV	76	22	25	31
Ban Kruat	BKT5	mean	339	10.0	8.0	6.1
	n=30	SD	172	2.0	1.6	1.3
		CV	51	20	20	21
Khok Rahoei/BPP221	BPP1	mean	411	10.1	8.0	5.6
	n=10	SD	369	4.3	2.7	2.1
		CV	90	43	34	37

Cluster	Site		Weight (g)	Size (cm)		
				Length	Width	Thick
Ban Sai Tho8	STH8 M1	mean	1160	15.3	12.3	9.4
	n=25	SD	786	3.5	3.2	2.9
		CV	68	23	26	31
	STH8 M3	mean	1051	15.0	12.2	7.9
	n=15	SD	575	2.6	2.9	2.1
		CV	55	17	24	27
	STH8 M4	mean	856	10.0	13.4	7.6
	n=20	SD	357	1.4	2.0	1.4
		CV	42	14	15	19
	STH8 T1	mean	288	8.1	6.1	4.2
	n=58	SD	334	3.0	2.2	1.7
		CV	116	37	36	41
	STH8 T2	mean	447	7.4	9.9	5.1
	n=14	SD	142	1.7	3.4	1.2
		CV	32	23	34	24
Ban Sai Tho8/2	STH8/2 M1	mean	803	12.7	10.1	7.5
	n=10	SD	563	2.4	2.2	1.3
		CV	70	19	22	17
	STH8/2 M2	mean	512	11.7	9.3	6.6
	n=10	SD	178	1.7	1.2	0.8
		CV	35	15	13	12
	STH8/2 M3	mean	646	12.8	9.7	6.5
	n=30	SD	396	3.3	2.3	1.9
		CV	61	26	24	30
	STH8/2 M6	mean	676	12.9	10.0	7.2
	n=30	SD	308	2.4	1.8	1.6
		CV	46	19.0	17.6	21.9

Cluster	Site		Weight (g)	Size (cm)		
				Length	Width	Thick
Ban Sai Tho10	STH10 S	mean	711	13.2	10.0	7.0
	n=30	SD	284	2.3	1.7	1.7
		CV	40	17	16	24
	STH10 B	mean	605	12.5	9.2	5.6
	n=30	SD	238	2.1	1.5	1.4
		CV	39	17	17	25
	STH10 D	mean	672	13.0	9.5	6.3
	n=5	SD	281	2.3	1.7	0.7
		CV	42	18	18	11

Appendix G The result of the examination of three types of slag (dense, semi-porous, and porous slag)

Cluster	Deposit	Total samples examined	Dense	%	Semi	%	Porous	%
KY	**4**	25	1	4	17	68	7	28
NC	**4**	29	1	3	23	79	5	17
KSK	**1**	30	1	3	17	57	12	40
KDT	**1**	15	-	-	12	80	3	20
	2	47	9	19	20	43	18	38
	3	30	-	-	28	93	2	7
	7	28	1	4	18	64	9	32
BKT	**5**	30	3	10	22	73	5	17
STH8	**M1**	30	2	7	25	83	3	10
	M3	15	-	-	15	100	-	-
	M4	20	-	-	18	90	2	10
STH8/2	**M3**	30	1	3	25	83	4	13
	M6	30	5	17	22	73	3	10
STH10	**E**	30	1	3	26	87	3	10
	S	30	11	37	15	50	4	13

Appendix H Normalised WD-XRF data for all samples as given by Department of Geosciences, University of Fribourg, Switzerland

Laterite	Context				Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	Cluster	Site		Level	wt%														
KDT2e001	KDT	KDT 2	TP1	L3-4 92-109	0.02	0.26	13.80	21.68	0.90	0.09	0.02	0.10	0.14	bdl	1.26	0.15	0.08	0.17	61.16
KDT2e002					0.02	0.24	13.33	23.66	0.84	0.05	0.02	0.09	0.12	bdl	1.35	0.18	0.09	0.18	59.64
STH8e001	STH8	STH 8 T1	T1	L5 90-100	0.01	0.07	13.41	47.04	0.39	0.03	bdl	0.08	0.13	bdl	0.47	0.12	0.05	1.75	35.25
STH8e002			T1	L6 100-100	0.01	0.05	10.65	30.02	0.26	0.02	bdl	0.07	0.09	bdl	0.30	0.12	0.06	0.07	58.10
STH8e003			T1		0.01	0.06	11.16	37.47	0.27	0.03	bdl	0.08	0.15	bdl	0.34	0.16	0.04	0.32	49.66
STH8e004			T1	L3 70-80	0.01	0.28	7.79	12.38	0.19	bdl	0.01	0.03	0.87	bdl	0.30	0.21	0.04	0.01	77.77
STH8e005			T1	L10 140-150	0.01	0.13	8.44	48.05	0.14	0.02	bdl	0.06	0.15	bdl	0.29	0.11	0.02	0.02	42.39
STH8e006			T2	L8 170-180	0.01	0.05	11.04	46.77	0.23	0.03	bdl	0.06	0.12	bdl	0.36	0.10	0.04	0.01	41.06
STH8-5LAT		geology	near mound 5		0.04	0.07	11.00	46.43	0.05	0.05	0.02	0.09	0.03	bdl	0.60	0.14	0.10	0.21	40.89
BPPLAT	BPP221	geology	surface near a pond		0.03	0.15	7.79	56.21	0.03	0.07	0.01	0.22	0.05	bdl	0.37	0.05	0.05	2.66	31.44
BKTLAT	KDT		surface		0.04	0.10	11.79	39.40	0.07	0.06	0.02	0.09	0.07	bdl	0.42	0.22	0.05	0.20	47.27

Laterite	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																																					wt%
KDT2e001	276	bdl	16	488	65	bdl	bdl	bdl	bdl	18	18	16	365	28	161	61	29	bdl	bdl	bdl	bdl	bdl	237	bdl	69	bdl	bdl	69	bdl	bdl	12	13	bdl	21	bdl	bdl	bdl	92.20
KDT2e002	277	bdl	13	366	48	bdl	bdl	bdl	bdl	17	8	5.7	366	35	123	41	49	bdl	bdl	bdl	bdl	10	234	15	241	26	bdl	87	bdl	bdl	41	16	bdl	bdl	bdl	bdl	bdl	95.50
STH8e001	355	16	112	56	32	1	2	bdl	bdl	15	17	24	702	4	94	59	45	bdl	bdl	bdl	bdl	104	4520	bdl	5020	bdl	bdl	46	bdl	bdl	bdl	6	29	969	bdl	bdl	bdl	81.80
STH8e002	309	9	256	116	38	bdl	86	bdl	bdl	12	6	32	319	4	163	47	19	22	bdl	17	bdl	1	73	5	141	38	bdl	142	bdl	93	14	5	bdl	69	3	bdl	bdl	85.60
STH8e003	235	bdl	294	68	16	4	112	bdl	bdl	16	10	21	486	4	167	44	48	13	bdl	bdl	bdl	20	687	bdl	178	bdl	bdl	42	bdl	bdl	6	bdl	bdl	91	5	bdl	bdl	83.50
STH8e004	173	bdl	48	21	42	3	231	bdl	bdl	bdl	30	18	284	bdl	144	49	23	5	bdl	3	bdl	3	82	23	65	69	bdl	bdl	bdl	bdl	15	17	31	57	bdl	bdl	bdl	88.20
STH8e005	202	bdl	40	34	11	bdl	142	bdl	bdl	22	18	13	754	bdl	157	22	15	bdl	bdl	bdl	bdl	34	98	bdl	bdl	bdl	bdl	1	bdl	bdl	bdl	4	5	59	9	bdl	bdl	81.80
STH8e006	179	bdl	110	45	20	bdl	40	bdl	bdl	14	5.8	22	503	11	154	23	21	26	bdl	20	bdl	bdl	153	23	bdl	bdl	bdl	63	bdl	74	8	bdl	bdl	15	bdl	bdl	bdl	81.40
STH8-5LAT	215	bdl	282	24	8	5	84	bdl	bdl	13	3.5	17	662	7	116	53	38	bdl	bdl	bdl	bdl	33	602	9	480	8	bdl	29	bdl	bdl	bdl	2	10	263	13	bdl	bdl	80.50
BPPLAT	268	bdl	139	58	20	bdl	bdl	bdl	bdl	28	41	30	519	12	25	28	19	13	bdl	34	bdl	148	6340	33	595	30	bdl	65	bdl	bdl	bdl	8	bdl	290	bdl	bdl	bdl	81.30
BKTLAT	329	bdl	113	22	25	bdl	29	bdl	bdl	11	7.6	10	538	4	183	61	37	1	bdl	bdl	bdl	bdl	612	32	48	bdl	bdl	79	bdl	bdl	18	bdl	2	73	3	bdl	bdl	88.10

Samples		Type	Context: Site	Context	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
					wt%														
Raw clay	KDTTS		KDT	clay from the Ta Sek stream	0.02	0.32	8.74	87.44	0.05	0.09	0.01	0.34	0.10	bdl	0.63	0.01	0.01	0.03	2.00
	KDTRF			clay from a nearby ricefield	0.04	0.76	5.41	90.09	0.01	0.07	bdl	0.12	1.71	bdl	0.35	0.00	0.03	0.09	1.07
	STH8TK		STH8	clay from a nearby stream	0.02	0.21	11.35	84.78	0.07	0.10	0.00	0.23	0.11	bdl	0.63	0.01	0.01	0.04	2.22
Technical ceramics	KDT2CP001	Clay plug	KDT2	excavated	0.10	0.33	12.13	82.94	0.06	0.07	0.00	0.14	0.23	bdl	0.57	0.02	0.02	0.14	3.09
	KDT2CP002	Clay plug		excavated	0.04	0.17	10.16	86.12	0.07	0.08	0.00	0.10	0.16	bdl	0.49	0.02	0.04	0.07	2.34
	KDT2FF001	Wall		excavated	0.01	0.21	11.40	84.38	0.10	0.13	0.00	0.11	0.39	bdl	0.48	0.01	0.05	0.06	2.45
	KDT2FF002	Wall		excavated	0.01	0.25	12.07	83.63	0.07	0.11	0.01	0.12	0.44	bdl	0.48	0.02	0.04	0.06	2.50
	KDT2FF003	Wall		excavated	0.03	0.31	13.87	79.77	0.29	0.08	0.01	0.31	0.41	bdl	0.63	0.02	0.02	0.24	3.80
	KDT2TU001	Tuyère		excavated	0.02	0.15	10.65	83.35	0.12	0.07	0.01	0.16	0.26	bdl	0.41	0.01	0.02	0.42	4.12
	KDT2TU002	Tuyère		excavated	0.03	0.16	11.15	84.90	0.09	0.05	0.01	0.16	0.42	bdl	0.64	0.01	0.02	0.02	2.14
	STH8T1TU	Tuyère	STH8 T1	excavated	0.02	0.14	15.54	80.34	0.48	0.06	0.01	0.26	0.38	bdl	0.57	0.01	0.02	0.00	2.00
	STH8T1CP	Clay plug	STH8 T1	excavated	0.00	0.14	14.52	80.27	0.11	0.05	0.00	0.10	0.17	bdl	0.58	0.02	0.02	0.02	3.84
	STH8T1FF	Furnace fragment	STH8 T1	excavated	0.01	0.15	11.97	85.22	0.19	0.04	0.00	0.15	0.24	bdl	0.43	0.01	0.01	0.01	1.40
	STH8M1CP	Clay plug	STH8 M1	surface	0.00	0.14	12.93	83.90	0.08	0.03	0.00	0.07	0.10	bdl	0.49	0.01	0.02	0.02	2.00
	STH8M1FF	Furnace fragment	STH8 M1	surface	0.03	0.12	14.22	82.65	0.13	0.06	0.01	0.25	0.19	bdl	0.55	0.01	0.02	0.00	1.62
	STH8T1H	Hearth wall	STH8 T1	excavated	0.03	0.29	12.78	80.32	1.48	0.07	0.00	0.46	0.92	bdl	0.50	0.01	0.02	0.05	2.86
	KY5TC	technical ceramic	KY5	surface	0.03	0.25	11.86	83.76	0.05	0.05	0.02	0.20	0.15	bdl	0.48	0.01	0.02	0.08	2.96
	KDT1FF	Furnace fragment	KDT1	surface	0.02	0.09	6.74	90.81	0.11	0.06	bdl	0.06	0.29	bdl	0.33	0.00	0.02	0.01	1.35
	KDT3TU	Tuyère	KDT3	surface	0.01	0.18	10.33	85.87	0.47	0.05	0.00	0.23	0.29	bdl	0.49	0.01	0.01	0.02	1.93
	KDT3CP	Clay plug	KDT3	surface	0.01	0.15	7.93	89.10	0.04	0.03	0.00	0.03	0.11	bdl	0.36	0.01	0.01	0.04	2.03
	STH8/2TC	technical ceramic	STH8/2 M6	surface	0.04	0.26	17.73	76.75	0.14	0.05	0.00	0.47	0.47	bdl	0.56	0.01	0.02	0.17	3.09
	STH10CP	Clay plug	STH10 S	surface	0.01	0.26	8.99	87.77	0.05	0.02	bdl	0.08	0.11	bdl	0.56	0.01	0.01	0.10	1.90
Domestic pottery	KDT2DP001	ET - dark brown - black core	KDT2	excavated	1.13	1.27	16.33	64.27	0.57	0.11	0.01	1.37	2.32	bdl	2.81	0.04	0.02	0.13	9.27
	KDT2DP002	ET - black burnished	KDT2	excavated	0.03	0.79	24.43	63.21	0.23	0.04	0.03	2.83	0.88	bdl	0.53	0.02	0.01	0.04	6.63
	KDT2DP003	ET - black burnished	KDT2	excavated	0.16	1.27	21.14	64.48	3.15	0.04	0.01	2.72	0.76	bdl	0.49	0.02	0.01	0.04	5.33
	KDT2DP004	ET - black burnished	KDT2	excavated	0.07	0.94	18.67	63.40	5.22	0.04	0.02	1.98	1.03	bdl	0.62	0.02	0.02	0.06	7.35
	KYKi	Orange stoneware	KY Kiln	surface	0.19	1.49	20.28	66.81	0.02	0.01	bdl	3.03	0.12	bdl	0.60	0.02	0.01	0.04	7.19
	NC4Kh	Khmer ceramic	NC4	surface	0.16	0.81	17.16	72.31	0.04	0.01	bdl	1.72	0.16	bdl	0.60	0.02	0.01	0.03	6.78

Samples		Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
		ppm																																					wt%
Raw clay	KDTTS	bdl	bdl	15	12	bdl	bdl	bdl	bdl	bdl	43	22	37	899	27	bdl	bdl	bdl	bdl	bdl	bdl	29	256	750	bdl	35	15	bdl	20	bdl	bdl	bdl	bdl	bdl	42	bdl	bdl	bdl	85.4
	KDTRF	24	12	bdl	bdl	bdl	bdl	bdl	bdl	bdl	20	107	20	792	16	bdl	bdl	14	bdl	bdl	bdl	29	308	798	bdl	bdl	bdl	bdl	32	bdl	bdl	bdl	bdl	bdl	25	bdl	bdl	bdl	83.5
	STH8TK	27	bdl	16	16	bdl	bdl	bdl	bdl	bdl	34	25	29	777	25	bdl	bdl	bdl	bdl	bdl	bdl	bdl	241	751	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	11	28	bdl	bdl	bdl	84.7
Technical ceramics	KDT2CP001	bdl	bdl	11	14	7.6	bdl	bdl	bdl	1.5	28	24	22	738	19	17	bdl	bdl	bdl	bdl	bdl	bdl	119	485	bdl	73	11	bdl	22	bdl	bdl	bdl	bdl	bdl	26	7	bdl	bdl	85.6
	KDT2CP002	bdl	bdl	11	9.7	13	8.9	bdl	bdl	bdl	17	13	11	827	20	38	bdl	6	bdl	bdl	bdl	9	148	343	bdl	4	bdl	bdl	18	8	bdl	bdl	5	13	30	9	bdl	bdl	82.7
	KDT2FF001	bdl	bdl	8.3	36	5.3	bdl	bdl	bdl	bdl	30	49	15	915	16	35	bdl	bdl	bdl	bdl	bdl	bdl	112	632	bdl	bdl	bdl	bdl	26	bdl	bdl	bdl	bdl	1	37	1	bdl	bdl	76.7
	KDT2FF002	19	14	7	37	13	bdl	bdl	bdl	bdl	30	55	15	911	19	5	bdl	4	bdl	bdl	bdl	bdl	110	630	bdl	81	bdl	bdl	23	bdl	bdl	bdl	bdl	bdl	32	8	bdl	bdl	77.1
	KDT2FF003	53	27	83	45	21	bdl	bdl	bdl	bdl	58	52	31	716	30	31	bdl	4	bdl	bdl	bdl	bdl	142	858	bdl	36	bdl	bdl	25	bdl	bdl	bdl	bdl	3	42	9	5	bdl	81.6
	KDT2TU001	52	16	23	31	2.2	5.7	bdl	bdl	2.5	21	33	18	833	15	10	bdl	bdl	bdl	bdl	bdl	bdl	144	1000	7	bdl	bdl	bdl	bdl	bdl	3	bdl	bdl	bdl	38	2	bdl	bdl	81.3
	KDT2TU002	35	31	26	33	11	bdl	bdl	bdl	1	34	68	19	828	22	30	bdl	bdl	bdl	bdl	bdl	bdl	133	822	bdl	bdl	bdl	bdl	21	bdl	12	bdl	bdl	bdl	36	5	bdl	bdl	81.2
	STH8T1TU	12	bdl	12	17	2.9	bdl	bdl	bdl	3	37	30	21	943	21	14	bdl	6	bdl	bdl	bdl	bdl	141	409	bdl	bdl	bdl	bdl	13	bdl	9	bdl	bdl	bdl	27	6	bdl	bdl	80.9
	STH8T1CP	23	bdl	16	27	16	4.7	bdl	bdl	bdl	21	15	21	943	17	32	bdl	4.9	bdl	bdl	bdl	bdl	157	328	bdl	bdl	bdl	bdl	29	bdl	bdl	3	bdl	5	23	bdl	bdl	bdl	84.4
	STH8T1FF	28	15	17	4.1	7.5	bdl	bdl	bdl	bdl	28	31	27	945	18	13	bdl	bdl	bdl	bdl	bdl	22	124	492	bdl	bdl	14	bdl	23	bdl	bdl	bdl	bdl	bdl	33	7	bdl	bdl	85
	STH8M1CP	21	17	14	bdl	17	bdl	bdl	bdl	bdl	12	9.3	14	868	15	14	bdl	bdl	bdl	bdl	65	88	333	530	bdl	bdl	30	bdl	9	bdl	bdl	bdl	bdl	bdl	18	8	bdl	bdl	85.5
	STH8M1FF	bdl	bdl	5.4	5.3	10	5.6	bdl	bdl	1.7	29	17	22	1010	23	29	3	2.3	bdl	bdl	bdl	bdl	109	326	1	bdl	bdl	bdl	30	bdl	bdl	bdl	bdl	bdl	24	3	bdl	bdl	82
	STH8T1H	bdl	bdl	14	53	8.9	3.3	bdl	bdl	1.5	84	74	47	657	19	23	bdl	13	bdl	bdl	bdl	bdl	154	944	bdl	10	28	bdl	9	bdl	bdl	4	bdl	2	33	6	bdl	bdl	82.8
	KY5TC	bdl	bdl	4.6	34	15	4.2	bdl	bdl	1.7	21	14	16	745	21	27	7.5	14	bdl	bdl	bdl	bdl	bdl	92	bdl	bdl	bdl	bdl	21	bdl	bdl	1	bdl	3	25	bdl	bdl	bdl	87.7
	KDT1FF	5	bdl	bdl	14	bdl	bdl	bdl	bdl	bdl	26	25	9.6	553	11	20	bdl	bdl	bdl	bdl	bdl	bdl	99	302	7	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	4	38	bdl	bdl	bdl	81.1
	KDT3TU	21	bdl	4.4	22	13	6.7	bdl	bdl	1.4	28	51	16	625	13	39	bdl	10	2.9	bdl	bdl	bdl	bdl	188	bdl	17	bdl	bdl	23	bdl	bdl	9	bdl	7	28	bdl	bdl	bdl	85.5
	KDT3CP	45	15	7.4	3.4	5.1	1.9	bdl	bdl	bdl	8.8	13	5	900	15	8	bdl	1.9	bdl	bdl	bdl	bdl	165	330	bdl	38	bdl	bdl	48	bdl	bdl	bdl	bdl	bdl	21	bdl	bdl	bdl	85.6
	STH8/2TC	77	44	25	24	16	bdl	bdl	bdl	bdl	61	28	36	996	18	26	6.9	18	bdl	bdl	bdl	bdl	199	597	bdl	155	11	bdl	27	12	bdl	bdl	bdl	bdl	29	11	bdl	bdl	82.5
	STH10CP	bdl	bdl	5.6	bdl	12	bdl	bdl	bdl	1.1	16	7.7	22	680	20	40	bdl	bdl	bdl	bdl	bdl	bdl	126	455	bdl	7	17	bdl	8	bdl	bdl	bdl	bdl	bdl	13	bdl	bdl	bdl	88.9
Domestic pottery	KDT2DP001	129	94	39	142	35	bdl	bdl	bdl	bdl	117	467	36	642	99	56	bdl	13	12	bdl	bdl	bdl	141	1380	bdl	45	29	bdl	29	bdl	bdl	bdl	bdl	bdl	12	bdl	bdl	bdl	84.7
	KDT2DP002	91	90	56	109	35	2.9	bdl	bdl	5	295	105	48	429	21	13	bdl	5	bdl	bdl	bdl	bdl	132	1500	bdl	39	39	bdl	1	bdl	bdl	bdl	bdl	6	31	4	1	bdl	84.6
	KDT2DP003	65	30	39	94	35	2.5	bdl	bdl	3.3	249	134	54	474	22	21	bdl	4	bdl	bdl	bdl	bdl	179	2460	bdl	43	bdl	bdl	31	18	bdl	bdl	bdl	7	31	bdl	bdl	bdl	89.1
	KDT2DP004	92	49	55	104	32	bdl	bdl	bdl	bdl	188	181	52	430	21	21	bdl	3	bdl	bdl	42	22	306	3840	bdl	189	24	bdl	28	bdl	bdl	bdl	bdl	bdl	30	bdl	bdl	bdl	87.3
	KYKi	99	22	23	81	31	1.5	bdl	bdl	bdl	212	35	42	470	26	30	bdl	5.8	bdl	bdl	bdl	bdl	144	697	bdl	68	26	bdl	12	2	bdl	bdl	bdl	bdl	38	bdl	bdl	bdl	92.4
	NC4Kh	90	26	8.9	58	22	bdl	bdl	bdl	bdl	142	53	50	556	19	47	23	30	bdl	bdl	bdl	2	106	673	10	14	7	bdl	bdl	bdl	16	bdl	bdl	bdl	36	bdl	bdl	bdl	91.9

Smelting slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	wt%														
KY4-001	0.03	0.45	14.58	35.12	0.24	0.05	0.00	0.55	2.03	bdl	0.94	0.18	0.10	0.68	44.71
KY4-002	0.04	0.23	14.73	33.04	0.22	0.06	0.01	0.39	0.51	bdl	1.03	0.17	0.12	0.74	48.40
KY4-003	0.08	0.47	12.59	32.98	0.32	0.07	0.02	0.48	2.06	bdl	0.97	0.15	0.11	1.10	48.03
KY4-004	0.04	0.33	14.00	33.50	0.23	0.07	0.00	0.70	1.28	bdl	1.06	0.15	0.09	2.48	45.15
KY4-005	0.06	0.24	13.13	35.63	0.18	0.04	0.00	0.47	1.10	bdl	0.71	0.15	0.09	0.81	47.05
KY4-006	0.02	0.24	13.08	30.94	0.25	0.05	0.01	0.53	0.82	bdl	1.05	0.15	0.09	0.52	51.90
KY4-007	0.03	0.35	14.20	32.37	0.19	0.04	bdl	0.42	1.76	bdl	1.00	0.14	0.11	0.51	48.51

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3
	ppm																	
KY4-001	287	bdl	5	25	43	bdl	bdl	bdl	bdl	31	94	12	570	20	113	36	60	bdl
KY4-002	270	bdl	6	51	44	bdl	bdl	bdl	bdl	35	29	12	543	19	117	26	22	bdl
KY4-003	418	bdl	121	76	45	bdl	bdl	bdl	bdl	48	137	25	608	26	55	59	bdl	bdl
KY4-004	296	bdl	18	43	35	bdl	bdl	bdl	bdl	46	88	18	623	17	64	27	12	bdl
KY4-005	301	bdl	bdl	24	30	2.6	11	bdl	bdl	36	48	6.5	547	6	141	40	27	bdl
KY4-006	411	bdl	14	79	44	bdl	bdl	bdl	bdl	49	55	13	528	15	135	55	36	bdl
KY4-007	376	bdl	60	101	39	bdl	bdl	bdl	bdl	36	106	11	561	19	147	42	51	31

Smelting slag	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																			wt%
KY4-001	bdl	bdl	bdl	42	1590	24	313	bdl	bdl	28	bdl	65	36	bdl	1	12	bdl	bdl	bdl	92.10
KY4-002	bdl	bdl	bdl	26	1310	bdl	420	60	bdl	38	bdl	70	3	bdl	11	51	bdl	bdl	bdl	94.00
KY4-003	bdl	bdl	bdl	72	3060	bdl	486	bdl	bdl	bdl	158	196	14	bdl	bdl	35	bdl	bdl	bdl	89.80
KY4-004	bdl	bdl	bdl	119	6870	bdl	824	bdl	bdl	43	bdl	84	16	bdl	14	28	bdl	bdl	bdl	89.40
KY4-005	bdl	bdl	bdl	31	1770	7	466	bdl	bdl	bdl	bdl	24	bdl	7	23	91	bdl	bdl	bdl	92.80
KY4-006	bdl	bdl	bdl	bdl	1370	53	346	bdl	bdl	77	28	37	bdl	11	bdl	26	bdl	bdl	bdl	91.20
KY4-007	bdl	40	bdl	118	1400	bdl	347	bdl	bdl	34	88	178	38	12	bdl	70	bdl	bdl	bdl	91.20

Smelting slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	wt%														
NC4-001	0.04	0.31	14.77	34.17	0.17	0.05	0.00	0.77	1.53	bdl	0.90	0.16	0.12	2.05	44.06
NC4-002	0.05	0.36	14.31	33.63	0.22	0.04	0.00	0.64	1.53	bdl	1.09	0.16	0.12	0.88	46.50
NC4-003	0.04	0.37	13.61	36.92	0.19	0.04	0.05	0.49	1.79	bdl	0.85	0.18	0.10	0.71	44.30
NC4-004	0.03	0.28	14.39	32.39	0.28	0.06	0.02	0.59	1.33	bdl	1.31	0.15	0.12	0.67	47.98
NC4-005	0.04	0.31	13.43	36.76	0.25	0.06	0.02	0.46	1.51	bdl	1.20	0.17	0.10	0.46	44.91
NC4-006	0.04	0.49	15.53	36.44	0.21	0.06	0.01	0.69	1.66	bdl	1.02	0.18	0.13	1.95	40.87
NC4-007	0.03	0.37	13.63	30.24	0.42	0.07	0.01	0.45	1.86	bdl	1.12	0.22	0.11	0.24	51.01
slb-NC4	0.04	0.44	15.07	41.12	0.40	0.06	0.01	0.81	3.15	bdl	0.96	0.15	0.08	0.64	36.75

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																																				wt%
NC4-001	398	bdl	46	33	20	bdl	bdl	bdl	bdl	46	153	20	603	21	102	47	16	bdl	bdl	bdl	bdl	148	6220	bdl	969	bdl	bdl	bdl	42	57	13	bdl	bdl	62	bdl	bdl	bdl	90.40
NC4-002	444	bdl	77	86	18	1.5	bdl	bdl	bdl	38	94	13	565	20	99	51	26	25	bdl	bdl	bdl	71	2200	bdl	456	21	bdl	bdl	117	281	bdl	bdl	5	43	bdl	bdl	8	94.30
NC4-003	314	bdl	48	38	29	bdl	bdl	bdl	bdl	31	117	9.9	572	15	87	22	19	bdl	bdl	5	bdl	35	1670	bdl	389	7	bdl	41	bdl	153	7	9	bdl	10	bdl	bdl	bdl	93.60
NC4-004	396	bdl	78	104	33	bdl	bdl	bdl	bdl	33	93	19	624	24	135	15	27	bdl	bdl	bdl	bdl	83	1730	51	300	bdl	bdl	25	93	203	15	bdl	bdl	bdl	bdl	bdl	bdl	91.60
NC4-005	376	bdl	82	95	39	bdl	bdl	bdl	bdl	34	119	19	606	26	103	44	57	bdl	5	bdl	bdl	bdl	949	27	237	bdl	bdl	69	84	185	31	13	11	11	bdl	bdl	bdl	91.60
NC4-006	306	bdl	5	12	35	4.7	bdl	bdl	bdl	38	143	16	607	23	109	53	46	bdl	bdl	bdl	bdl	89	4640	bdl	883	39	bdl	49	bdl	142	bdl	12	20	11	9	bdl	bdl	93.30
NC4-007	394	bdl	91	98	29	bdl	bdl	bdl	bdl	19	94	14	458	17	145	43	16	1	bdl	bdl	bdl	2	408	57	181	bdl	bdl	bdl	126	265	8	bdl	14	bdl	1	bdl	bdl	93.10
slb-NC4	288	bdl	bdl	12	29	bdl	bdl	bdl	bdl	36	157	22	520	24	95	28	20	bdl	bdl	bdl	bdl	61	1460	bdl	402	bdl	bdl	37	bdl	55	2	16	bdl	17	bdl	2	3	96.40

Smelting slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	wt%														
KSK1-001	0.03	0.37	13.57	40.76	0.26	0.07	0.00	0.54	1.55	bdl	0.90	0.16	0.09	1.55	39.52
KSK1-002	0.04	0.44	16.21	37.36	0.28	0.07	0.01	0.60	2.40	bdl	1.44	0.20	0.13	1.27	39.04
KSK1-003	0.03	0.24	14.86	33.36	0.23	0.05	0.00	0.36	0.38	bdl	1.12	0.17	0.10	0.69	47.97
KSK1-004	0.02	0.33	14.45	37.07	0.13	0.07	0.03	0.42	1.33	bdl	0.99	0.18	0.10	0.90	43.51
KSK1-005	0.05	0.37	15.87	35.13	0.29	0.09	0.02	0.76	0.86	bdl	1.23	0.20	0.15	1.34	43.05
KSK1-006	0.02	0.28	14.71	34.82	0.27	0.05	0.00	0.34	0.51	bdl	1.14	0.20	0.16	0.92	46.23
KSK1-007	0.03	0.42	15.52	33.60	0.34	0.07	0.01	0.33	1.57	bdl	1.37	0.18	0.12	0.77	45.32

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3
	ppm																	
KSK1-001	394	bdl	72	99	16	2.8	bdl	bdl	bdl	43	120	13	609	18	127	57	31	1
KSK1-002	295	bdl	2	37	20	bdl	bdl	bdl	bdl	40	194	22	662	34	88	39	21	13
KSK1-003	390	bdl	86	91	40	bdl	bdl	bdl	bdl	24	32	20	541	25	80	36	41	bdl
KSK1-004	386	bdl	76	90	21	2.2	bdl	bdl	bdl	33	101	14	632	23	160	66	21	bdl
KSK1-005	364	bdl	82	70	29	bdl	bdl	bdl	bdl	46	62	23	601	28	122	48	39	bdl
KSK1-006	243	bdl	3	56	43	bdl	bdl	bdl	bdl	26	34	13	544	19	87	43	10	1
KSK1-007	351	bdl	31	57	38	bdl	11	bdl	bdl	28	131	22	648	31	116	47	44	bdl

Smelting slag	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																			wt%
KSK1-001	bdl	bdl	bdl	50	3180	42	894	bdl	bdl	17	140	300	bdl	bdl	bdl	32	bdl	bdl	bdl	92.70
KSK1-002	bdl	bdl	bdl	28	2760	bdl	692	5	bdl	27	bdl	131	2	bdl	bdl	11	bdl	bdl	bdl	91.10
KSK1-003	bdl	bdl	bdl	98	1660	29	568	bdl	bdl	74	133	166	13	bdl	bdl	52	bdl	bdl	bdl	92.30
KSK1-004	bdl	bdl	bdl	44	2100	8	489	bdl	bdl	bdl	110	297	11	bdl	bdl	26	bdl	bdl	bdl	89.70
KSK1-005	bdl	bdl	bdl	33	3320	20	610	bdl	bdl	31	93	318	bdl	bdl	bdl	30	bdl	bdl	bdl	92.90
KSK1-006	bdl	bdl	bdl	32	1910	bdl	451	bdl	bdl	bdl	bdl	24	bdl	bdl	bdl	60	bdl	bdl	bdl	92.70
KSK1-007	bdl	bdl	bdl	88	1750	bdl	349	bdl	bdl	bdl	bdl	bdl	16	16	bdl	29	bdl	bdl	bdl	90.00

Smelting slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	wt%														
KDT1-001	0.04	0.71	16.94	38.99	0.23	0.08	0.00	0.54	4.22	bdl	1.83	0.19	0.10	0.36	35.51
KDT1-002	0.03	0.55	14.07	34.74	0.35	0.07	0.00	0.41	2.29	bdl	1.35	0.16	0.09	0.32	45.33
KDT1-003	0.02	0.37	14.56	34.68	0.38	0.06	bdl	0.53	1.73	bdl	1.31	0.16	0.08	0.20	45.74
KDT1-004	0.03	0.31	13.39	31.25	0.37	0.09	bdl	0.29	0.27	bdl	1.81	0.16	0.09	0.47	51.17
KDT1-005	0.04	0.40	15.78	32.83	0.37	0.06	0.00	0.55	0.65	bdl	1.91	0.18	0.11	0.50	46.30

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																																					wt%
KDT1-001	306	bdl	46	63	18	bdl	8	1.3	bdl	37	280	17	639	49	124	38	33	bdl	bdl	bdl	bdl	4	660	bdl	12	bdl	bdl	21	73	271	bdl	bdl	bdl	bdl	bdl	bdl	bdl	91.30
KDT1-002	368	bdl	71	84	22	1.6	bdl	bdl	bdl	32	152	14	524	29	128	35	22	bdl	bdl	bdl	bdl	4	530	1	25	bdl	bdl	39	104	178	2	bdl	bdl	7	bdl	bdl	bdl	91.30
KDT1-003	282	bdl	27	37	30	2.8	bdl	bdl	bdl	41	91	21	466	32	138	47	36	15	bdl	5	bdl	bdl	314	18	18	bdl	bdl	53	bdl	143	bdl	3	9	3	bdl	bdl	bdl	93.40
KDT1-004	414	bdl	80	100	30	bdl	bdl	bdl	bdl	28	24	19	539	47	87	41	32	bdl	bdl	bdl	bdl	77	995	37	182	23	bdl	bdl	90	244	bdl	bdl	bdl	1	bdl	bdl	bdl	92.00
KDT1-005	416	bdl	77	116	30	bdl	bdl	bdl	bdl	46	44	20	573	50	127	44	43	bdl	bdl	bdl	bdl	26	881	83	284	24	bdl	17	136	289	2	bdl	bdl	2	bdl	bdl	bdl	92.90

Smelting slag	Context		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	Level	Furnace	wt%														
KDT2-001	L2		0.03	0.28	12.64	29.44	0.36	0.04	bdl	0.36	0.40	bdl	1.47	0.15	0.09	0.25	54.31
KDT2-002	L3		0.01	0.27	13.27	28.38	0.53	0.08	0.02	0.42	0.54	bdl	1.75	0.16	0.10	0.17	54.08
KDT2-003			0.02	0.36	13.61	29.12	0.48	0.04	0.00	0.33	1.88	bdl	1.58	0.18	0.12	0.51	51.41
KDT2-004	L4		0.04	0.24	13.28	29.73	0.38	0.07	0.00	0.31	0.80	bdl	1.72	0.17	0.10	0.51	52.38
KDT2-005	L5		0.04	0.35	13.21	37.12	0.56	0.12	0.00	0.60	0.89	bdl	1.38	0.18	0.12	0.44	44.72
KDT2-006			0.02	0.25	13.59	30.03	0.51	0.08	0.01	0.35	0.95	bdl	1.29	0.19	0.10	0.20	52.21
KDT2-007	L3-4 92-109	1	0.04	0.30	13.33	28.44	0.79	0.03	0.03	0.37	1.26	bdl	1.65	0.14	0.06	0.24	53.11
KDT2-008	L3-4 92-110	1	0.03	0.38	12.99	27.24	0.80	0.02	0.01	0.33	0.74	bdl	1.57	0.15	0.07	0.13	55.37
KDT2-009	L3-4 92-111	1	0.04	0.43	15.15	33.87	0.32	0.02	0.00	0.43	0.79	bdl	1.67	0.19	0.10	0.54	46.14
KDT2-010	L3-4 92-112	1	0.05	0.44	14.91	31.37	0.48	0.02	0.01	0.35	1.17	bdl	1.79	0.20	0.10	0.39	48.45
KDT2-011	L3-4 92-113	1	0.05	0.36	13.47	31.19	0.34	0.03	0.02	0.40	0.51	bdl	1.57	0.16	0.08	0.81	50.66
KDT2-012	L3-4 92-114	1	0.03	0.32	13.69	28.99	0.60	0.03	0.01	0.47	0.61	bdl	1.49	0.17	0.11	0.33	52.86
KDT2-013	L3-4 92-115	1	0.04	0.33	14.22	33.39	0.60	0.04	0.01	0.37	0.65	bdl	1.69	0.18	0.09	0.32	47.87
KDT2-014	L3-5 90-115	2	0.03	0.42	13.87	26.37	0.53	0.03	0.00	0.37	1.58	bdl	1.65	0.18	0.10	0.54	53.97
KDT2-015	L3-5 90-116	2	0.03	0.35	14.88	32.58	0.60	0.03	0.00	0.43	0.71	bdl	1.75	0.18	0.08	0.33	47.80
KDT2-016	L3-5 90-117	2	0.04	0.40	13.86	32.29	0.35	bdl	0.00	0.59	0.71	bdl	1.41	0.18	0.08	1.30	48.28
KDT2-017	L3-5 90-118	2	0.03	0.31	13.47	31.70	0.31	0.08	0.01	0.38	0.48	bdl	1.66	0.18	0.09	0.81	50.13
KDT2-018	L3-5 90-119	2	0.03	0.38	14.47	31.95	0.29	0.07	0.02	0.33	0.55	bdl	1.85	0.22	0.12	0.40	49.07
KDT2-019	L3-5 90-120	2	0.03	0.41	16.02	34.26	0.25	0.07	0.00	0.44	0.68	bdl	1.82	0.23	0.14	0.81	44.45
KDT2-020	L3-5 90-121	2	0.05	0.34	13.41	31.29	0.32	0.08	0.01	0.41	0.52	bdl	1.72	0.18	0.10	0.91	50.28
KDT2-021	L3-5 90-122	2	0.03	0.36	13.45	31.85	0.50	0.07	0.01	0.55	0.78	bdl	1.64	0.16	0.09	0.37	49.88
KDT2-022	L6		0.02	0.36	12.95	28.20	0.75	0.08	bdl	0.24	2.28	bdl	1.64	0.15	0.07	0.29	52.69
KDT2-023			0.02	0.31	12.84	28.65	0.75	0.09	0.00	0.23	2.02	bdl	1.69	0.13	0.06	0.28	52.63

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Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																																					wt%
KDT2-001	267	bdl	bdl	78	26	2	bdl	bdl	bdl	29	25	13	474	35	156	25	21	bdl	bdl	bdl	bdl	15	418	72	97	bdl	bdl	bdl	bdl	57	1	3	4	2	bdl	bdl	bdl	92.20
KDT2-002	416	bdl	67	92	56	bdl	bdl	bdl	bdl	31	37	15	521	41	132	67	34	7	bdl	bdl	bdl	11	359	6	45	16	bdl	28	155	243	11	3	5	1	5	bdl	bdl	91.50
KDT2-003	441	bdl	109	137	25	1	bdl	bdl	bdl	29	130	20	512	40	170	35	27	bdl	bdl	bdl	bdl	109	1280	36	160	bdl	bdl	bdl	149	272	11	9	bdl	21	bdl	bdl	bdl	91.90
KDT2-004	416	bdl	109	109	34	bdl	bdl	bdl	bdl	25	31	22	562	41	140	41	55	7	bdl	bdl	bdl	5	758	13	173	bdl	bdl	bdl	137	201	bdl	bdl	bdl	7	bdl	bdl	bdl	87.40
KDT2-005	296	bdl	47	70	27	5.9	bdl	bdl	bdl	73	91	17	576	19	102	22	bdl	bdl	bdl	bdl	bdl	67	952	bdl	302	14	bdl	32	bdl	68	bdl	bdl	3	15	bdl	bdl	bdl	88.60
KDT2-006	402	bdl	112	114	36	2	bdl	bdl	bdl	44	46	17	441	30	161	45	41	bdl	bdl	bdl	bdl	bdl	285	19	30	bdl	bdl	21	164	243	bdl	bdl	bdl	4	bdl	bdl	bdl	91.70
KDT2-007	395	bdl	17	35	41	bdl	4	bdl	bdl	25	57	11	456	40	146	47	31	bdl	bdl	bdl	bdl	bdl	462	bdl	254	72	bdl	59	31	21	43	2	bdl	bdl	bdl	bdl	bdl	95.90
KDT2-008	328	bdl	13	86	35	7.9	bdl	bdl	bdl	29	44	5.9	466	31	145	48	47	21	bdl	bdl	bdl	23	145	65	264	50	bdl	bdl	bdl	83	bdl	bdl	bdl	16	12	bdl	bdl	95.20
KDT2-009	366	bdl	69	112	23	bdl	bdl	bdl	bdl	37	54	18	526	40	150	44	42	bdl	bdl	bdl	bdl	37	1040	81	319	2	bdl	bdl	136	168	bdl	bdl	bdl	8	bdl	bdl	bdl	93.80
KDT2-010	419	bdl	59	78	23	3.8	bdl	bdl	bdl	28	89	18	519	38	139	44	35	14	bdl	bdl	bdl	15	636	bdl	379	72	bdl	bdl	79	87	bdl	bdl	bdl	5	bdl	bdl	bdl	95.90
KDT2-011	427	bdl	122	110	14	bdl	bdl	bdl	bdl	35	38	19	458	32	134	66	48	18	bdl	bdl	bdl	bdl	1150	33	272	75	bdl	39	148	224	bdl	bdl	bdl	17	bdl	bdl	bdl	96.00
KDT2-012	429	bdl	111	139	51	1.8	bdl	bdl	bdl	37	33	10	451	31	130	36	28	7	bdl	bdl	bdl	49	482	43	397	106	bdl	58	131	223	2	bdl	bdl	1	bdl	bdl	bdl	96.80
KDT2-013	242	bdl	18	46	32	bdl	bdl	bdl	bdl	30	50	18	495	35	141	45	30	8	bdl	bdl	bdl	bdl	424	76	249	55	bdl	60	bdl	8	27	10	bdl	1	bdl	bdl	bdl	95.80
KDT2-014	412	bdl	83	96	47	bdl	bdl	bdl	bdl	29	117	15	456	33	138	10	19	bdl	bdl	bdl	20	45	1080	52	316	108	bdl	42	169	237	17	bdl	bdl	6	bdl	bdl	bdl	95.60
KDT2-015	392	bdl	37	68	41	bdl	bdl	bdl	bdl	33	57	20	511	42	113	53	39	26	bdl	bdl	bdl	43	515	41	75	54	bdl	52	43	44	bdl	bdl	bdl	bdl	bdl	bdl	bdl	95.90
KDT2-016	363	bdl	47	97	24	5	bdl	bdl	bdl	48	40	24	544	30	114	36	34	bdl	bdl	bdl	bdl	85	2310	32	783	10	bdl	bdl	112	245	bdl	5	4	7	14	bdl	bdl	93.50
KDT2-017	427	bdl	101	92	38	bdl	bdl	bdl	bdl	36	46	28	510	34	108	54	20	1	bdl	1	bdl	38	1210	60	320	133	bdl	77	134	243	20	bdl	bdl	bdl	bdl	bdl	bdl	93.40
KDT2-018	273	bdl	89	45	35	bdl	bdl	bdl	bdl	30	42	14	583	45	107	40	30	17	bdl	4	bdl	bdl	586	35	257	120	bdl	52	bdl	132	27	3	bdl	21	bdl	bdl	bdl	90.10
KDT2-019	389	bdl	106	104	29	bdl	bdl	bdl	bdl	44	54	29	628	44	144	30	25	bdl	16	bdl	bdl	25	1320	27	468	47	bdl	73	179	276	1	bdl	bdl	5	1	bdl	bdl	90.20
KDT2-020	432	bdl	108	114	31	bdl	bdl	bdl	bdl	36	47	31	513	41	108	10	2	bdl	13	bdl	bdl	35	1370	91	436	74	bdl	43	99	273	2	bdl	bdl	bdl	14	bdl	bdl	92.80
KDT2-021	417	bdl	89	109	28	1.9	6	bdl	bdl	48	49	18	542	43	132	47	13	3	bdl	bdl	bdl	bdl	532	25	382	62	bdl	bdl	137	201	18	bdl	6	bdl	bdl	bdl	bdl	92.40
KDT2-022	397	bdl	89	99	34	4	bdl	bdl	bdl	17	172	14	510	30	138	25	14	bdl	bdl	bdl	bdl	72	668	35	184	15	bdl	49	116	142	17	bdl	bdl	14	bdl	bdl	bdl	91.70
KDT2-023	415	bdl	100	109	34	bdl	bdl	bdl	bdl	23	152	10	504	41	166	34	13	bdl	bdl	3	bdl	114	711	30	134	31	bdl	bdl	119	245	bdl	bdl	bdl	bdl	1	bdl	1	92.60

Smelting slag	Context		Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	Level	Furnace	wt%														
KDT2-024	L7		0.02	0.32	13.83	25.79	0.75	0.05	0.00	0.33	1.26	bdl	1.85	0.18	0.11	0.61	54.59
KDT2-025			0.01	0.43	10.35	25.70	0.51	0.10	0.02	0.40	2.26	bdl	1.27	0.17	0.10	0.12	58.37
KDT2-026	L8		0.02	0.30	12.53	32.50	0.23	0.04	bdl	0.33	1.05	bdl	1.44	0.16	0.09	0.48	50.53
KDT2-027			0.03	0.20	12.65	32.53	0.14	0.03	0.01	0.22	0.56	bdl	1.34	0.16	0.09	0.61	51.12
KDT2-028	L9		0.03	0.60	13.51	27.96	0.33	0.06	0.01	0.42	1.13	bdl	1.52	0.17	0.09	0.13	53.83
KDT2-029			0.04	0.39	12.79	31.04	0.48	0.04	bdl	0.32	1.59	bdl	1.72	0.13	0.06	0.35	50.78
KDT2-030	L10		0.02	0.23	12.62	30.39	0.68	0.12	0.02	0.26	0.90	bdl	1.50	0.16	0.08	0.16	52.67
KDT2-031			0.02	0.29	12.27	29.07	0.54	0.06	bdl	0.32	0.80	bdl	1.10	0.12	0.07	0.83	54.12
KDT2-032	L9-10/11	4	0.03	0.50	15.31	35.84	0.43	0.07	0.00	0.45	2.12	bdl	1.74	0.18	0.10	0.30	42.68
KDT2-033		4	0.03	0.23	13.68	32.90	0.37	0.08	0.02	0.48	0.37	bdl	1.46	0.18	0.11	0.51	49.27
KDT2-034	L14		0.02	0.35	14.90	33.52	0.18	0.04	bdl	0.40	0.96	bdl	1.27	0.19	0.11	0.32	47.48
KDT2-035			0.03	0.28	13.84	35.09	0.21	0.06	0.00	0.30	0.83	bdl	1.85	0.19	0.13	0.20	46.83
KDT2-036	L17		0.04	0.58	12.34	36.33	0.18	0.09	0.01	0.76	0.77	bdl	0.54	0.17	0.09	0.29	47.54
KDT2-037			0.06	0.44	13.92	33.60	0.12	0.03	0.00	0.62	0.33	bdl	0.79	0.15	0.08	0.81	48.64
KDT2-038	L18		0.02	0.65	13.00	41.06	0.15	0.08	0.00	0.43	0.57	bdl	1.13	0.22	0.09	0.41	41.94
KDT2-039			0.03	0.59	15.95	33.79	0.16	0.04	bdl	0.41	0.78	bdl	1.38	0.20	0.14	0.21	46.06
KDT2-040	L19		0.03	0.81	14.69	33.76	0.18	0.07	0.01	0.64	0.66	bdl	1.05	0.23	0.11	0.36	47.13
KDT2-041			0.02	0.53	16.62	35.94	0.13	0.02	bdl	0.30	0.30	bdl	1.42	0.21	0.16	0.20	43.90
KDT2-042			0.02	0.66	13.84	37.03	0.22	0.10	0.00	0.52	1.12	bdl	1.12	0.23	0.14	0.18	44.62
KDT2-043	L21		0.03	0.38	12.98	36.96	0.12	0.07	bdl	0.36	0.94	bdl	0.92	0.21	0.08	0.51	46.12
KDT2-044			0.03	0.50	14.87	34.70	0.19	0.08	bdl	0.47	1.86	bdl	1.75	0.21	0.13	0.32	44.59
KDT2-045	L23		0.07	0.53	14.07	36.80	0.19	0.10	0.01	0.54	0.84	bdl	1.16	0.18	0.14	0.73	44.23
KDT2-046			0.02	0.35	14.15	34.17	0.19	0.06	0.00	0.34	1.12	bdl	1.56	0.19	0.11	0.21	47.29
KDT2-047			0.02	0.52	13.90	33.39	0.22	0.07	0.00	0.41	1.73	bdl	1.57	0.20	0.12	0.23	47.37
slb-KDT2TP2	TP2		0.03	0.71	16.17	40.34	0.56	0.04	0.01	0.57	3.89	bdl	1.44	0.15	0.09	0.18	35.59

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																																					wt%
KDT2-024	390	bdl	41	84	42	4.4	bdl	bdl	bdl	21	94	13	483	45	83	38	43	bdl	bdl	bdl	bdl	44	1250	32	359	20	bdl	bdl	bdl	117	2	bdl	20	23	bdl	bdl	bdl	93.00
KDT2-025	358	bdl	15	14	45	bdl	bdl	bdl	1.1	41	217	16	445	38	176	56	32	bdl	bdl	bdl	bdl	bdl	207	bdl	118	64	bdl	66	bdl	bdl	33	bdl	8	6	5	bdl	bdl	87.60
KDT2-026	445	bdl	105	88	26	bdl	bdl	bdl	bdl	26	93	19	573	28	99	41	55	8	bdl	bdl	bdl	47	967	21	84	bdl	bdl	43	142	286	bdl	bdl	bdl	16	bdl	bdl	bdl	90.20
KDT2-027	289	bdl	28	60	22	7	bdl	1.4	bdl	18	20	30	605	28	125	46	41	14	bdl	bdl	bdl	bdl	1120	61	469	1	bdl	25	bdl	104	bdl	bdl	1	19	4	bdl	bdl	89.50
KDT2-028	346	bdl	bdl	74	39	9	bdl	bdl	bdl	39	87	16	504	37	176	49	58	7	bdl	bdl	bdl	30	210	bdl	66	32	bdl	107	38	169	29	bdl	bdl	bdl	bdl	bdl	bdl	90.20
KDT2-029	451	bdl	84	98	36	bdl	bdl	bdl	bdl	23	110	21	510	49	136	39	35	12	bdl	bdl	17	34	592	40	108	16	bdl	47	137	247	5	bdl	bdl	6	bdl	bdl	bdl	91.50
KDT2-030	431	bdl	86	119	39	8.1	bdl	bdl	bdl	23	74	14	429	34	125	30	48	27	bdl	9	bdl	12	235	65	14	bdl	bdl	bdl	137	179	5	11	28	bdl	bdl	bdl	bdl	92.50
KDT2-031	471	bdl	28	71	40	bdl	bdl	bdl	5.9	34	46	12	474	25	122	41	47	13	bdl	10	bdl	19	1830	42	357	2	bdl	bdl	107	119	7	bdl	bdl	30	16	bdl	bdl	91.80
KDT2-032	386	bdl	54	98	35	bdl	bdl	bdl	bdl	36	164	23	583	44	109	14	19	bdl	bdl	bdl	bdl	15	501	bdl	6	5	bdl	33	85	163	bdl	bdl	bdl	bdl	2	bdl	bdl	91.80
KDT2-033	430	bdl	99	110	36	bdl	bdl	bdl	bdl	38	36	11	540	30	117	49	17	bdl	bdl	bdl	bdl	15	1060	57	231	bdl	bdl	21	137	187	7	bdl	bdl	12	3	bdl	bdl	85.60
KDT2-034	381	bdl	77	75	31	bdl	bdl	bdl	bdl	31	56	29	610	28	107	56	23	13	bdl	bdl	bdl	bdl	571	32	145	29	bdl	43	88	228	bdl	bdl	bdl	bdl	bdl	bdl	bdl	91.80
KDT2-035	373	bdl	57	28	25	bdl	bdl	bdl	bdl	bdl	bdl	bdl	612	49	95	30	31	bdl	bdl	bdl	bdl	37	276	bdl	49	bdl	bdl	24	37	131	bdl	bdl	bdl	bdl	bdl	bdl	bdl	89.10
KDT2-036	380	bdl	86	74	24	bdl	bdl	bdl	bdl	58	53	19	583	14	182	42	23	1	bdl	bdl	bdl	7	825	23	141	bdl	bdl	44	92	189	7	bdl	bdl	19	bdl	bdl	bdl	87.10
KDT2-037	416	bdl	103	110	16	12	bdl	bdl	bdl	46	37	19	493	17	97	47	21	bdl	bdl	bdl	bdl	bdl	1780	48	467	bdl	bdl	bdl	130	332	bdl	bdl	bdl	40	14	bdl	bdl	92.40
KDT2-038	364	bdl	41	20	28	5.5	bdl	bdl	bdl	41	39	31	686	25	142	48	37	bdl	bdl	10	bdl	bdl	825	39	109	2	bdl	33	29	143	12	bdl	12	bdl	bdl	bdl	bdl	88.10
KDT2-039	405	bdl	109	101	25	bdl	bdl	bdl	bdl	34	52	23	654	40	114	31	25	bdl	bdl	bdl	bdl	12	469	4	190	bdl	bdl	bdl	108	340	bdl	bdl	bdl	20	bdl	bdl	bdl	91.60
KDT2-040	361	bdl	bdl	bdl	22	bdl	bdl	bdl	bdl	45	51	38	697	35	132	43	20	bdl	bdl	bdl	bdl	11	769	30	541	25	bdl	29	bdl	101	10	11	9	16	bdl	12	bdl	87.60
KDT2-041	372	bdl	79	83	39	bdl	bdl	bdl	bdl	29	27	34	644	29	187	33	56	bdl	bdl	bdl	bdl	25	343	bdl	159	31	bdl	46	85	273	bdl	bdl	bdl	11	bdl	bdl	bdl	91.60
KDT2-042	246	bdl	bdl	27	31	bdl	bdl	bdl	bdl	45	58	17	680	34	100	37	16	bdl	bdl	bdl	bdl	3	326	bdl	146	bdl	bdl	41	bdl	84	17	bdl	bdl	1	bdl	bdl	bdl	89.20
KDT2-043	402	bdl	81	88	2	3	bdl	bdl	bdl	34	49	19	665	9	144	28	5	bdl	bdl	bdl	bdl	16	1030	9	324	bdl	bdl	bdl	129	305	bdl	bdl	bdl	5	bdl	2	bdl	89.00
KDT2-044	385	bdl	89	77	35	bdl	bdl	bdl	bdl	41	96	38	652	37	125	30	31	bdl	bdl	bdl	bdl	77	694	bdl	148	bdl	bdl	9	96	297	bdl	13	bdl	6	bdl	bdl	bdl	89.90
KDT2-045	385	bdl	112	82	26	2.3	bdl	bdl	bdl	42	46	14	599	24	95	43	32	bdl	9	bdl	bdl	13	1760	2	445	bdl	bdl	28	153	203	bdl	bdl	bdl	7	bdl	bdl	bdl	90.70
KDT2-046	368	bdl	72	104	53	1	bdl	bdl	bdl	22	93	20	552	38	92	33	15	bdl	bdl	bdl	bdl	4	392	13	122	28	bdl	65	110	259	13	3	bdl	bdl	bdl	bdl	bdl	90.60
KDT2-047	385	bdl	31	56	35	bdl	5	bdl	bdl	29	135	20	613	35	134	39	9	20	bdl	bdl	bdl	bdl	501	12	207	65	bdl	58	61	81	23	bdl	bdl	bdl	16	bdl	bdl	88.10
slb-KDT2TP	317	bdl	106	65	20	2.1	bdl	bdl	bdl	37	232	10	482	29	129	34	33	12	bdl	bdl	bdl	30	367	bdl	161	32	bdl	30	110	156	bdl	bdl	9	bdl	bdl	bdl	bdl	99.50

Smelting slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	wt%														
KDT3-001	0.02	0.38	13.65	37.51	0.39	0.03	bdl	0.45	1.51	bdl	1.09	0.19	0.13	0.73	43.50
KDT3-002	0.02	0.40	14.55	35.50	0.25	0.04	bdl	0.48	1.72	bdl	1.21	0.18	0.08	1.27	43.78
KDT3-003	0.03	0.50	14.89	34.50	0.27	0.05	0.00	0.72	1.06	bdl	1.13	0.19	0.15	0.81	45.33
KDT3-004	0.03	0.54	14.57	41.41	0.49	0.08	0.00	0.89	2.04	bdl	1.22	0.16	0.10	0.63	37.51
KDT3-005	0.03	0.31	13.72	36.41	0.20	0.04	0.00	0.60	1.15	bdl	1.05	0.17	0.10	0.76	45.07

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3
	ppm																	
KDT3-001	400	bdl	105	112	32	bdl	bdl	bdl	78	25	98	14	513	22	104	46	29	bdl
KDT3-002	420	bdl	67	81	30	9	bdl	bdl	bdl	22	103	28	485	26	146	28	19	bdl
KDT3-003	308	bdl	23	47	31	bdl	bdl	bdl	bdl	44	45	19	522	23	104	24	16	bdl
KDT3-004	284	bdl	bdl	24	29	bdl	bdl	bdl	bdl	62	73	11	502	26	131	49	33	8
KDT3-005	405	bdl	65	89	24	9.5	bdl	1.4	bdl	34	98	11	579	13	120	21	38	16

Smelting slag	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																			wt%
KDT3-001	bdl	bdl	bdl	42	1570	36	534	bdl	bdl	26	155	184	bdl	bdl	bdl	9	bdl	bdl	bdl	97.40
KDT3-002	bdl	bdl	bdl	41	2470	bdl	766	18	bdl	63	111	229	bdl	bdl	4	51	bdl	bdl	bdl	94.30
KDT3-003	bdl	4	bdl	71	1890	bdl	406	bdl	bdl	46	bdl	226	6	5	2	22	bdl	bdl	bdl	91.30
KDT3-004	bdl	bdl	bdl	57	1410	32	305	bdl	bdl	60	bdl	46	7	12	bdl	11	bdl	bdl	bdl	97.80
KDT3-005	bdl	bdl	bdl	16	1570	19	489	1	bdl	53	87	220	bdl	bdl	bdl	19	2	bdl	bdl	

Smelting slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	wt%														
BKT5-001	0.03	0.52	14.64	39.39	0.13	bdl	0.00	0.55	0.95	bdl	0.91	0.19	0.16	1.48	40.50
BKT5-002	0.02	0.47	14.93	32.36	0.31	0.06	0.01	0.76	1.50	bdl	1.25	0.16	0.12	0.53	47.15
BKT5-003	0.02	0.49	13.41	40.52	0.15	0.06	bdl	0.59	0.94	bdl	0.67	0.15	0.09	2.26	39.86
BKT5-004	0.03	0.32	13.37	34.16	0.20	0.06	0.01	0.50	1.03	bdl	0.84	0.19	0.14	0.51	48.33
BKT5-005	0.02	0.23	11.95	30.00	0.65	0.05	0.00	0.34	0.93	bdl	1.28	0.13	0.07	0.57	53.38
BKT5-006	0.03	0.29	13.80	31.29	0.24	0.03	bdl	0.40	1.18	bdl	0.90	0.15	0.10	0.79	50.39
BKT5-007	0.03	0.28	14.11	31.71	0.26	0.05	0.01	0.36	0.95	bdl	1.04	0.17	0.10	0.81	49.79

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3
	ppm																	
BKT5-001	289	bdl	23	49	12	bdl	bdl	bdl	bdl	47	58	34	687	23	135	39	44	bdl
BKT5-002	402	bdl	117	108	63	bdl	bdl	bdl	bdl	51	69	10	585	22	81	46	41	bdl
BKT5-003	309	bdl	bdl	31	25	9.5	bdl	bdl	bdl	53	48	15	563	13	51	36	37	bdl
BKT5-004	415	bdl	99	110	37	bdl	bdl	bdl	bdl	47	65	15	589	15	149	40	35	bdl
BKT5-005	457	bdl	111	167	46	bdl	bdl	bdl	bdl	33	42	21	518	33	139	48	54	bdl
BKT5-006	448	bdl	91	113	29	9	5	bdl	bdl	32	75	8.6	506	16	108	33	27	16
BKT5-007	287	bdl	6	75	30	5	16	bdl	bdl	34	58	8.4	538	18	105	41	29	1

Smelting slag	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																			wt%
BKT5-001	bdl	bdl	bdl	45	3090	19	630	bdl	bdl	bdl	bdl	265	bdl	bdl	bdl	27	bdl	bdl	bdl	91.00
BKT5-002	bdl	bdl	bdl	21	1330	73	338	bdl	bdl	33	155	230	26	bdl	bdl	40	bdl	bdl	bdl	92.40
BKT5-003	bdl	3	bdl	88	5070	28	1070	bdl	bdl	bdl	bdl	222	24	7	13	80	bdl	bdl	bdl	93.10
BKT5-004	bdl	bdl	bdl	35	937	4	293	24	bdl	46	127	236	10	1	bdl	37	bdl	bdl	bdl	92.60
BKT5-005	bdl	17	bdl	60	1440	65	426	18	bdl	bdl	150	235	21	bdl	15	50	bdl	bdl	bdl	91.70
BKT5-006	bdl	bdl	bdl	39	1770	55	360	bdl	bdl	bdl	126	252	bdl	5	7	42	19	bdl	bdl	94.10
BKT5-007	bdl	bdl	bdl	1	1760	bdl	474	4	bdl	bdl	bdl	43	bdl	14	15	79	bdl	bdl	bdl	94.20

Smelting slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	wt%														
STH8-001	0.03	0.27	13.02	38.34	0.11	0.05	bdl	0.40	0.68	bdl	0.40	0.18	0.06	0.10	46.18
STH8-002	0.03	0.58	14.38	36.16	0.20	0.08	0.00	0.68	0.39	bdl	0.44	0.21	0.12	1.18	45.05
STH8-003	0.03	0.52	13.13	38.56	0.21	0.09	0.00	0.57	2.09	bdl	0.43	0.17	0.10	0.34	43.40
STH8-004	0.03	0.45	14.40	40.59	0.25	0.08	0.00	0.59	1.85	bdl	0.48	0.24	0.05	0.28	40.49
STH8-005	0.02	0.21	12.57	34.68	0.08	0.04	bdl	0.32	0.83	bdl	0.41	0.20	0.05	0.05	50.36
STH8-006	0.03	0.20	12.87	33.78	0.10	0.04	bdl	0.42	1.00	bdl	0.39	0.09	0.05	0.63	50.08
STH8-007	0.01	0.25	13.11	32.50	0.12	0.05	bdl	0.50	0.98	bdl	0.37	0.17	0.07	0.21	51.36

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3
	ppm																	
STH8-001	406	bdl	66	36	12	bdl	bdl	bdl	bdl	33	30	19	490	7.8	123	30	26	23
STH8-002	381	bdl	84	58	29	bdl	bdl	bdl	bdl	56	23	48	717	6	131	44	54	9
STH8-003	362	bdl	99	71	25	bdl	bdl	bdl	bdl	69	85	41	609	bdl	133	46	44	bdl
STH8-004	337	bdl	60	55	20	2.4	bdl	bdl	1.3	34	48	35	640	11	88	44	20	bdl
STH8-005	407	bdl	94	74	15	3.9	bdl	bdl	bdl	20	35	16	476	6.1	135	47	41	bdl
STH8-006	441	bdl	66	81	14	bdl	bdl	bdl	bdl	52	49	13	342	4.2	135	45	20	bdl
STH8-007	438	bdl	105	93	35	bdl	bdl	bdl	bdl	44	28	22	487	bdl	147	39	46	bdl

Smelting slag	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																			wt%
STH8-001	bdl	bdl	bdl	bdl	184	bdl	bdl	bdl	bdl	76	62	174	bdl	bdl	bdl	bdl	bdl	bdl	bdl	94.00
STH8-002	bdl	bdl	bdl	45	2070	bdl	852	37	bdl	1	108	221	bdl	bdl	5	24	1	bdl	bdl	89.40
STH8-003	bdl	bdl	bdl	13	949	bdl	579	76	bdl	45	135	168	bdl	bdl	bdl	16	bdl	bdl	bdl	85.90
STH8-004	bdl	bdl	bdl	20	410	bdl	112	bdl	bdl	27	89	147	11	bdl	6	bdl	bdl	1	bdl	91.20
STH8-005	bdl	bdl	bdl	bdl	81	bdl	bdl	bdl	bdl	bdl	92	204	18	9	8	bdl	bdl	bdl	bdl	93.60
STH8-006	bdl	bdl	bdl	72	1290	15	151	29	bdl	bdl	143	285	bdl	bdl	bdl	16	9	bdl	bdl	95.00
STH8-007	bdl	bdl	bdl	50	508	bdl	396	bdl	bdl	61	155	231	bdl	bdl	bdl	43	bdl	bdl	bdl	91.70

Smelting slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	wt%														
STH8/2-001	0.03	0.26	13.35	36.33	0.12	0.09	bdl	0.44	0.81	bdl	0.62	0.24	0.10	0.35	47.00
STH8/2-002	0.02	0.39	13.50	34.08	0.08	0.03	bdl	0.42	2.13	bdl	0.39	0.21	0.08	0.18	48.28
STH8/2-003	0.02	0.23	13.06	36.20	0.08	0.06	0.00	0.31	0.66	bdl	0.35	0.16	0.08	0.10	48.50
STH8/2-004	0.02	0.23	13.28	33.21	0.08	0.10	bdl	0.44	0.82	bdl	0.36	0.15	0.06	0.05	51.06
STH8/2-005	0.02	0.23	14.45	36.22	0.09	0.06	0.01	0.48	0.52	bdl	0.38	0.22	0.10	0.09	47.00
STH8/2-006	0.03	0.29	12.62	31.56	0.08	0.05	bdl	0.56	1.62	bdl	0.38	0.18	0.07	0.07	52.35
STH8/2-007	0.02	0.20	13.97	33.46	0.10	0.05	0.00	0.41	0.57	bdl	0.35	0.20	0.07	0.06	50.39
slb-STH8/2M6	0.02	0.24	10.77	44.78	0.17	0.18	0.05	0.42	1.13	bdl	0.43	0.19	0.10	0.10	41.23

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3	SnO_2
	ppm																		
STH8/2-001	402	bdl	142	89	6	bdl	bdl	bdl	bdl	34	43	16	496	7	124	24	11	bdl	bdl
STH8/2-002	421	bdl	132	79	21	bdl	bdl	bdl	bdl	29	44	8.2	400	3.4	81	20	34	bdl	bdl
STH8/2-003	371	bdl	114	73	36	bdl	bdl	bdl	bdl	27	23	30	372	bdl	134	32	bdl	bdl	bdl
STH8/2-004	363	bdl	98	bdl	bdl	bdl	47	bdl	bdl	53	47	18	320	bdl	85	33	39	bdl	bdl
STH8/2-005	292	bdl	72	44	29	bdl	bdl	bdl	bdl	63	25	22	373	6.3	133	40	36	bdl	bdl
STH8/2-006	269	bdl	65	24	28	bdl	bdl	bdl	bdl	53	69	39	375	bdl	147	43	29	bdl	bdl
STH8/2-007	374	bdl	124	69	13	bdl	bdl	2.4	bdl	43	43	12	323	6.2	146	21	26	3	bdl
slb-STH8/2M6	345	bdl	177	43	38	12	79	bdl	5.7	39	55	23	434	9.8	115	51	34	3	bdl

Smelting slag	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																		wt%
STH8/2-001	bdl	bdl	5	759	bdl	251	34	bdl	bdl	127	228	bdl	bdl	bdl	15	bdl	bdl	bdl	92.30
STH8/2-002	bdl	bdl	6	264	bdl	210	17	bdl	26	127	442	6	bdl	bdl	7	bdl	bdl	bdl	95.10
STH8/2-003	bdl	bdl	55	422	bdl	71	bdl	bdl	72	115	159	27	bdl	12	bdl	bdl	bdl	bdl	91.50
STH8/2-004	bdl	bdl	14	231	bdl	68	bdl	bdl	bdl	bdl	46	bdl	bdl	bdl	28	bdl	bdl	bdl	91.10
STH8/2-005	bdl	16	bdl	83	bdl	53	bdl	bdl	44	bdl	163	9	3	bdl	2	bdl	14	bdl	94.60
STH8/2-006	bdl	bdl	bdl	245	bdl	108	40	bdl	41	bdl	24	15	bdl	bdl	11	bdl	bdl	bdl	88.60
STH8/2-007	bdl	bdl	bdl	74	bdl	57	bdl	bdl	bdl	108	203	bdl	bdl	bdl	20	bdl	11	bdl	94.00
slb-STH8/2M6	bdl	bdl	21	262	9	114	2	bdl	73	83	105	16	9	bdl	bdl	bdl	8	bdl	97.40

Smelting slag	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	wt%														
STH10-001	0.02	0.15	11.66	29.81	0.08	0.04	bdl	0.20	0.30	bdl	0.41	0.18	0.04	0.05	56.86
STH10-002	0.02	0.26	13.62	33.92	0.08	0.04	bdl	0.39	0.22	bdl	0.39	0.19	0.06	0.08	50.54
STH10-003	0.02	0.28	12.66	37.75	0.06	0.04	bdl	0.32	0.30	bdl	0.37	0.22	0.07	0.07	47.68
STH10-004	0.01	0.32	13.34	32.31	0.07	0.05	bdl	0.30	0.44	bdl	0.45	0.21	0.06	0.06	52.24
STH10-005	0.01	0.29	13.21	35.23	0.06	bdl	bdl	0.28	0.30	bdl	0.44	0.22	0.06	0.06	49.65
STH10-006	0.02	0.33	10.74	35.64	0.19	0.17	0.01	0.33	0.68	bdl	0.44	0.20	0.05	0.09	50.93
STH10-007	0.02	0.11	12.69	33.71	0.08	0.07	0.01	0.29	0.52	bdl	0.46	0.22	0.06	0.05	51.57

Smelting slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3
	ppm																	
STH10-001	421	bdl	107	81	25	bdl	bdl	bdl	bdl	11	19	14	423	bdl	128	39	29	bdl
STH10-002	393	bdl	97	91	23	bdl	bdl	bdl	bdl	17	10	11	476	2	112	37	29	bdl
STH10-003	367	bdl	89	72	34	bdl	bdl	bdl	bdl	20	18	16	374	bdl	135	33	36	bdl
STH10-004	381	bdl	17	bdl	23	bdl	bdl	bdl	bdl	bdl	bdl	bdl	538	bdl	130	23	bdl	bdl
STH10-005	438	bdl	30	26	22	9.2	bdl	bdl	bdl	19	14	11	594	9	133	35	29	bdl
STH10-006	390	bdl	27	12	bdl	15	32	bdl	bdl	31	19	12	632	bdl	136	55	49	bdl
STH10-007	260	bdl	11	22	bdl	bdl	bdl	bdl	bdl	21	26	13	508	bdl	124	59	28	bdl

Smelting slag	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
	ppm																			wt%
STH10-001	bdl	bdl	bdl	bdl	177	53	45	bdl	bdl	59	137	239	bdl	bdl	bdl	bdl	bdl	bdl	bdl	93.60
STH10-002	bdl	bdl	bdl	30	160	3	114	bdl	bdl	51	92	253	9	bdl	bdl	1	4	bdl	bdl	94.10
STH10-003	bdl	1	bdl	3	182	6	24	bdl	bdl	49	116	208	10	bdl	bdl	9	bdl	bdl	bdl	94.90
STH10-004	bdl	bdl	bdl	bdl	187	bdl	90	bdl	bdl	68	21	74	17	bdl	bdl	bdl	bdl	bdl	bdl	90.60
STH10-005	bdl	bdl	bdl	46	125	48	73	bdl	bdl	bdl	88	138	7	5	14	bdl	1	3	bdl	93.20
STH10-006	bdl	bdl	bdl	94	366	45	142	bdl	bdl	bdl	45	40	31	10	bdl	bdl	bdl	bdl	bdl	86.90
STH10-007	bdl	bdl	bdl	77	250	bdl	40	bdl	bdl	bdl	bdl	18	bdl	bdl	bdl	21	bdl	bdl	bdl	90.20

Smithing slag	Context				Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	Sc_2O_3	TiO_2	V_2O_5	Cr_2O_3	MnO	Fe_2O_3
	Site	Pit		Excavation level	wt%														
KDT2/7-001	KDT2	TP1	Furnace 7	L31-32/33 375-390	0.07	0.71	5.16	21.59	1.43	0.14	0.02	1.08	1.23	bdl	0.36	0.05	0.03	0.23	67.73
KDT2/7-002	KDT2	TP1	Furnace 7	L31-32/33 375-390	0.09	0.53	4.91	25.58	0.85	0.08	0.01	0.69	0.90	bdl	0.29	0.06	0.03	0.14	65.65
KDT2/7-003	KDT2	TP1	Furnace 7	L31-32/33 375-390	0.07	0.70	6.51	23.45	2.73	0.10	0.00	1.40	1.85	bdl	0.64	0.07	0.05	0.29	61.90
KDT2/7-004	KDT2	TP1	Furnace 7	L31-32/33 375-390	0.03	0.67	15.16	34.09	0.24	0.13	0.01	0.36	1.50	bdl	1.27	0.25	0.16	0.49	45.30
KDT2/7-005	KDT2	TP1	Furnace 7	L31-32/33 375-390	0.06	1.12	2.94	27.51	1.31	0.10	0.00	1.45	1.97	bdl	0.18	0.03	0.02	0.26	62.83
KDT2/7-006	KDT2	TP1	Furnace 7	L31-32/33 375-390	0.08	0.48	5.43	17.88	2.08	0.10	0.01	0.83	1.04	bdl	0.42	0.06	0.05	0.38	70.94
STH8sm001	STH8	T1			0.06	0.63	7.08	23.48	0.49	0.10	0.02	1.17	2.12	bdl	0.17	0.11	0.04	0.24	64.09
STH8sm002	STH8	T1		L3 70-80	0.01	0.22	9.39	71.03	0.37	0.02	0.00	0.39	0.32	bdl	0.47	0.07	0.05	0.06	17.38
STH8sm003	STH8	T1		L4 80-90	0.03	0.31	4.07	20.19	0.33	0.14	0.08	0.62	0.46	bdl	0.11	0.05	0.03	0.06	73.35
STH8sm004	STH8	T1		L5 90-100	0.03	1.36	1.43	23.23	1.19	0.09	0.00	0.88	3.25	bdl	0.07	0.01	0.01	0.09	68.19
STH8sm005	STH8	T1		L5 90-100	0.05	0.96	9.10	33.94	0.37	0.08	0.00	2.63	2.52	bdl	0.23	0.09	0.03	0.16	49.58
STH8sm006	STH8	T1		L6 100-110	0.05	0.82	6.62	23.61	2.13	0.11	0.01	0.79	1.85	bdl	0.81	0.08	0.06	0.60	62.23
STH8sm007	STH8				0.02	0.26	13.94	34.09	0.17	0.02	0.01	0.39	0.76	bdl	0.46	0.21	0.07	0.06	49.36
STH8sm008	STH8	T2		L2 110-120	0.05	0.53	6.10	23.46	0.45	0.18	0.03	0.72	1.39	bdl	0.16	0.08	0.03	0.25	66.35
STH8sm009	STH8	T2		L7 160-170	0.08	0.40	4.83	24.04	0.95	0.14	0.02	0.65	1.14	bdl	0.33	0.05	0.04	0.06	67.14
STH8sm010	STH8	T2			0.04	0.50	8.02	27.52	0.39	0.10	0.01	1.24	1.51	bdl	0.22	0.11	0.04	0.47	59.44
STH8sm011	STH8	T2			0.04	0.64	4.90	27.69	0.79	0.11	0.01	1.31	1.06	bdl	0.24	0.05	0.03	0.14	62.83
STH8sm012	STH8	T2		L8 170-180	0.11	0.18	1.33	26.06	0.54	0.06	bdl	0.39	0.49	bdl	0.05	0.01	0.01	0.02	70.62

Smithing slag	Co_3O_4	NiO	CuO	ZnO	Ga_2O_3	GeO_2	As_2O_3	SeO_2	Br	Rb_2O	SrO	Y_2O_3	ZrO_2	Nb_2O_5	MoO_3	Ag_2O	CdO	In_2O_3	SnO_2	Sb_2O_3	TeO_2	Cs_2O	BaO	La_2O_3	CeO_2	Nd_2O_3	Sm_2O_3	HfO_2	Ta_2O_5	WO_3	PtO_2	Au	HgO	PbO	Bi_2O_3	ThO_2	U_3O_8	Total
															ppm																							wt%
KDT2/7-001	480	bdl	42	33	39	3	bdl	bdl	bdl	89	64	5	158	bdl	124	54	27	4	bdl	5	bdl	35	500	21	52	76	bdl	bdl	42	152	13	bdl	21	bdl	bdl	bdl	bdl	95.40
KDT2/7-002	460	bdl	5	16	30	bdl	bdl	bdl	bdl	69	54	6.4	191	1.9	114	49	43	23	bdl	bdl	bdl	13	331	106	149	76	bdl	bdl	87	106	28	14	bdl	bdl	bdl	bdl	bdl	95.00
KDT2/7-003	444	bdl	63	71	58	3	bdl	bdl	bdl	101	96	8	213	15	130	30	8	bdl	bdl	bdl	bdl	bdl	429	67	189	28	bdl	63	135	257	4	bdl	bdl	3	bdl	bdl	bdl	95.70
KDT2/7-004	374	bdl	68	71	37	6	7	bdl	bdl	39	112	51	733	31	120	49	42	bdl	bdl	bdl	bdl	18	919	bdl	550	63	bdl	44	89	212	14	bdl	bdl	9	bdl	bdl	6	88.10
KDT2/7-005	523	bdl	53	5	38	bdl	bdl	bdl	bdl	197	118	4	121	5.8	95	46	33	14	bdl	bdl	bdl	bdl	617	59	78	2	bdl	95	23	152	24	bdl	bdl	10	bdl	bdl	bdl	94.40
KDT2/7-006	493	bdl	64	25	44	bdl	bdl	bdl	bdl	63	63	bdl	137	1.4	143	44	53	23	bdl	bdl	bdl	1	677	92	94	48	bdl	bdl	66	203	bdl	bdl	bdl	bdl	8	bdl	bdl	95.90
STH8sm001	328	bdl	47	24	7	bdl	3	bdl	bdl	101	99	4	236	bdl	123	34	30	bdl	bdl	bdl	bdl	29	377	42	389	25	bdl	52	bdl	148	bdl	bdl	15	bdl	bdl	bdl	bdl	93.90
STH8sm002	172	bdl	39	59	19	bdl	bdl	bdl	bdl	43	24	25	553	bdl	48	bdl	18	bdl	bdl	bdl	bdl	238	743	21	62	bdl	bdl	16	54	237	bdl	bdl	bdl	bdl	bdl	bdl	bdl	93.00
STH8sm003	485	bdl	144	62	50	bdl	56	bdl	bdl	99	11	bdl	105	bdl	125	50	31	bdl	bdl	bdl	bdl	33	280	13	bdl	bdl	bdl	72	141	178	17	bdl	bdl	bdl	bdl	bdl	bdl	
STH8sm004	475	bdl	62	1	30	bdl	3	bdl	bdl	71	162	bdl	46	bdl	132	56	42	8	bdl	bdl	bdl	15	421	31	bdl	bdl	bdl	bdl	bdl	91	bdl	bdl	bdl	3	1	bdl	bdl	94.60
STH8sm005	403	bdl	40	15	34	bdl	bdl	bdl	bdl	284	122	18	340	bdl	100	41	27	bdl	12	bdl	bdl	80	590	bdl	94	bdl	bdl	41	49	114	30	13	bdl	bdl	11	bdl	bdl	94.50
STH8sm006	461	bdl	bdl	4	66	bdl	bdl	bdl	bdl	69	102	5.8	297	21	82	26	10	bdl	bdl	bdl	bdl	bdl	941	72	66	24	bdl	79	23	50	33	17	bdl	5	bdl	bdl	bdl	94.80
STH8sm007	420	bdl	83	69	15	9.9	bdl	bdl	bdl	32	35	11	486	bdl	133	35	41	6	bdl	8	bdl	8	139	37	31	9	bdl	bdl	134	202	4	10	bdl	bdl	4	bdl	6	96.90
STH8sm008	427	bdl	55	15	20	bdl	bdl	bdl	bdl	78	80	bdl	218	bdl	202	42	30	bdl	bdl	bdl	bdl	60	589	30	246	23	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	bdl	93.50
STH8sm009	425	bdl	24	bdl	33	bdl	bdl	bdl	bdl	63	46	bdl	205	bdl	144	48	39	bdl	bdl	bdl	bdl	21	287	13	bdl	bdl	bdl	bdl	15	103	bdl	bdl	bdl	bdl	10	bdl	bdl	94.20
STH8sm010	438	bdl	83	62	49	bdl	bdl	bdl	bdl	141	98	13	367	bdl	132	48	25	33	bdl	2	bdl	24	1170	65	879	23	bdl	28	134	199	20	bdl	bdl	bdl	bdl	bdl	bdl	94.70
STH8sm011	474	bdl	51	7	30	bdl	bdl	bdl	bdl	105	45	bdl	161	bdl	138	41	28	bdl	bdl	bdl	bdl	48	343	26	13	bdl	bdl	69	19	25	35	15	22	bdl	bdl	bdl	bdl	95.90
STH8sm012	692	bdl	180	bdl	7	7	bdl	bdl	bdl	38	17	bdl	110	bdl	142	33	18	bdl	bdl	bdl	bdl	bdl	49	103	88	45	bdl	17	bdl	26	bdl	11	13	bdl	bdl	bdl	bdl	95.20

Appendix I Normalised chemical compositions of "the black phase"

Sample	wt%	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	MnO	FeO	Original analytical total
NC003	Analysis 1	27.6	43.1	bdl	0.8	1.0	1.5	bdl	0.5	25.6	101.8
	Analysis 2	19.4	49.5	0.5	0.8	2.7	1.8	bdl	0.6	24.6	102.0
	Analysis 3	22.1	48.1	bdl	0.8	2.2	1.7	bdl	0.6	24.7	102.6
STH10-005	Analysis 1	24.5	51.0	bdl	0.7	bdl	0.8	bdl	bdl	23.0	98.6
	Analysis 2	24.4	50.5	bdl	0.8	bdl	1.2	bdl	bdl	23.2	98.7
	Analysis 3	24.2	50.5	bdl	0.7	bdl	1.0	0.5	bdl	23.2	100.0
	Analysis 4	28.3	43.5	bdl	0.5	bdl	0.8	0.9	bdl	26.1	102.9
	Analysis 5	29.1	42.1	bdl	0.6	bdl	0.6	1.2	bdl	26.3	100.0
STH10-005	Analysis 1	23.9	51.8	bdl	0.5	bdl	1.1	bdl	bdl	22.7	98.9
	Analysis 2	25.2	50.0	bdl	0.6	bdl	0.9	0.6	bdl	22.7	99.6
	Analysis 3	24.3	50.8	bdl	0.5	bdl	1.1	bdl	bdl	23.3	99.5
	Analysis 4	24.4	50.7	bdl	0.6	bdl	1.0	0.5	bdl	22.8	98.8
STH8-001	Analysis 1	28.6	43.3	bdl	0.4	0.4	0.9	1.0	bdl	25.4	100.3
	Analysis 2	19.5	56.0	bdl	1.0	1.9	0.9	bdl	bdl	20.8	96.2
	Analysis 3	17.4	56.7	bdl	1.0	2.2	1.0	bdl	bdl	21.7	97.7
STH10-003	Analysis 1	27.3	45.4	bdl	0.5	bdl	0.7	0.7	bdl	25.5	99.5
	Analysis 2	25.8	47.3	bdl	0.6	bdl	0.5	0.8	bdl	25.0	99.9
	Analysis 3	24.4	51.5	bdl	1.0	bdl	0.9	bdl	bdl	22.3	101.3
STH8-006	Analysis 1	27.0	45.3	bdl	1.2	0.9	1.0	bdl	bdl	24.6	99.3
	Analysis 2	22.3	50.1	bdl	1.2	1.7	1.1	bdl	bdl	23.5	100.6
	Analysis 3	25.9	47.0	bdl	1.4	1.1	0.8	bdl	bdl	23.7	100.6

Note: Each analysis was performed by a SEM-EDS spot analysis of the crystal.

Appendix J Normalised WD-XRF data for the slag samples of each slag deposit presented in Chapter 8

Khok Yang 4

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
KY4-001	15.36	37.00	0.25	0.58	2.14	0.99	0.19	0.11	0.72	42.39	5	26	33	99	601	1675	25	330	bdl	2.1
KY4-002	15.55	34.87	0.23	0.41	0.53	1.09	0.18	0.13	0.78	45.97	6	54	37	31	573	1383	bdl	443	63	1.8
KY4-003	13.33	34.92	0.34	0.51	2.18	1.03	0.16	0.12	1.16	45.77	128	80	51	145	644	3240	bdl	515	bdl	1.8
KY4-004	14.74	35.27	0.24	0.74	1.35	1.12	0.16	0.10	2.61	42.78	19	45	48	93	656	7234	bdl	868	bdl	1.9
KY4-005	13.84	37.55	0.19	0.49	1.16	0.75	0.16	0.10	0.85	44.61	bdl	25	38	51	576	1865	7	491	bdl	2.0
KY4-006	13.86	32.78	0.27	0.56	0.87	1.11	0.16	0.10	0.55	49.48	15	84	52	58	559	1452	56	367	bdl	1.6
KY4-007	15.01	34.22	0.20	0.44	1.86	1.06	0.14	0.11	0.53	46.14	63	107	38	112	593	1480	bdl	367	bdl	1.8
Mean	14.53	35.23	0.24	0.53	1.44	1.02	0.16	0.11	1.03	45.30	35	60	42	84	600	2618	-	483	-	1.8
SD%	0.9	1.6	0.0	0.1	0.6	0.1	0.0	0.0	0.7	2.4	46.1	31.0	7.8	39.7	36.6	2134.2	-	183.1	-	0.2
CV%	6	5	20	20	44	13	9	11	71	5	133	51	18	47	6	82	-	38	-	9

Nong Chik 4

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
NC4-001	15.53	35.93	0.18	0.81	1.61	0.95	0.17	0.13	2.16	41.69	48	35	48	161	634	6540	bdl	1019	bdl	2.0
NC4-002	15.10	35.49	0.23	0.67	1.61	1.15	0.16	0.13	0.93	44.15	81	91	40	99	596	2321	bdl	481	22	1.9
NC4-003	14.33	38.87	0.20	0.52	1.88	0.89	0.19	0.11	0.74	41.97	51	40	33	123	602	1758	bdl	410	7	2.2
NC4-004	15.19	34.20	0.30	0.63	1.40	1.38	0.16	0.12	0.71	45.59	82	110	35	98	659	1827	54	317	bdl	1.8
NC4-005	14.14	38.71	0.26	0.49	1.59	1.26	0.18	0.11	0.48	42.55	86	100	36	125	638	999	28	250	bdl	2.1
NC4-006	16.31	38.27	0.22	0.73	1.74	1.07	0.18	0.14	2.05	38.62	5	13	40	150	637	4873	bdl	927	41	2.2
NC4-007	14.45	32.06	0.44	0.47	1.97	1.19	0.23	0.12	0.25	48.66	96	104	20	100	486	433	60	192	bdl	1.6
Mean	15.01	36.22	0.26	0.62	1.69	1.13	0.18	0.12	1.05	43.32	64	70	36	122	608	2679	-	514	-	2.0
SD%	0.8	2.6	0.1	0.1	0.2	0.2	0.0	0.0	0.8	3.2	31.8	39.8	8.7	25.5	58.0	2209.6	-	329.2	-	0.2
CV%	5	7	34	21	11	15	13	9	72	7	49	57	24	21	10	82	-	64	-	13

Khok Sakon 1

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
KSK1-001	14.22	42.70	0.28	0.57	1.62	0.95	0.16	0.10	1.62	37.25	75	104	45	126	638	3331	44	937	bdl	2.6
KSK1-002	16.98	39.14	0.29	0.63	2.51	1.51	0.21	0.14	1.33	36.80	2	39	42	203	694	2891	bdl	725	5	2.5
KSK1-003	15.69	35.21	0.24	0.38	0.40	1.18	0.18	0.11	0.72	45.56	91	96	25	34	571	1752	31	600	bdl	1.8
KSK1-004	15.20	38.99	0.14	0.44	1.40	1.04	0.19	0.11	0.95	41.18	80	95	35	106	665	2209	8	514	bdl	2.2
KSK1-005	16.70	36.96	0.30	0.80	0.91	1.29	0.21	0.16	1.41	40.75	86	74	48	65	632	3493	21	642	bdl	2.1
KSK1-006	15.49	36.67	0.28	0.36	0.53	1.20	0.21	0.16	0.97	43.81	3	59	27	36	573	2011	bdl	475	bdl	2.0
KSK1-007	16.36	35.42	0.36	0.34	1.65	1.44	0.19	0.12	0.81	42.98	33	60	30	138	683	1845	bdl	368	bdl	1.9
Mean	15.80	37.87	0.27	0.50	1.29	1.23	0.19	0.13	1.12	41.19	53	75	36	101	636	2505	18	609	-	2.2
SD%	1.0	2.6	0.1	0.2	0.7	0.2	0.0	0.0	0.3	3.3	39.3	24.0	9.1	61.3	49.3	723.6	14.3	185.7	-	0.3
CV%	6	7	26	34	57	16	10	20	30	8	74	32	25	61	8	29	78	31	-	14

Khao Din Tai 1

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
KDT1-001	17.73	40.82	0.24	0.56	4.42	1.92	0.20	0.10	0.37	33.45	48	66	39	293	669	691	bdl	13	bdl	2.9
KDT1-002	14.85	36.68	0.37	0.44	2.42	1.43	0.17	0.09	0.34	43.06	75	89	34	160	553	560	1	26	bdl	2.0
KDT1-003	15.34	36.55	0.40	0.56	1.82	1.38	0.17	0.09	0.21	43.37	28	39	43	96	491	331	19	19	bdl	2.0
KDT1-004	14.19	33.13	0.39	0.31	0.29	1.92	0.17	0.10	0.49	48.81	85	106	30	25	571	1055	39	193	24	1.6
KDT1-005	16.66	34.65	0.39	0.58	0.68	2.02	0.19	0.12	0.52	43.97	81	122	49	46	605	930	88	300	25	1.9
Mean	15.76	36.36	0.36	0.49	1.93	1.73	0.18	0.10	0.39	42.53	64	84	39	124	578	713	30	110	-	2
SD%	1.4	2.9	0.1	0.1	1.6	0.3	0.0	0.0	0.1	5.6	24.3	32.9	7.5	107.8	65.6	288.9	36.1	130.0	-	0.5
CV%	9	8	18	24	85	17	9	11	32	13	38	39	19	87	11	41	122	118	-	23

Khao Din Tai 2

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
KDT2-001	13.43	31.27	0.38	0.38	0.42	1.56	0.16	0.10	0.27	51.90	bdl	83	31	27	503	444	76	103	bdl	1.4
KDT2-002	14.10	30.16	0.57	0.45	0.57	1.86	0.17	0.10	0.18	51.71	71	98	33	39	554	382	6	48	17	1.4
KDT2-003	14.43	30.88	0.50	0.35	1.99	1.68	0.19	0.13	0.54	49.05	116	145	31	138	543	1357	38	170	bdl	1.5
KDT2-004	14.08	31.53	0.40	0.33	0.84	1.82	0.18	0.10	0.54	49.98	116	116	27	33	596	804	14	183	bdl	1.5
KDT2-005	13.91	39.09	0.59	0.63	0.94	1.45	0.19	0.13	0.46	42.38	49	74	77	96	607	1003	bdl	318	15	2.2
KDT2-006	14.41	31.85	0.54	0.37	1.01	1.37	0.20	0.11	0.21	49.82	119	121	47	49	468	302	20	32	bdl	1.5
KDT2-007	14.15	30.19	0.84	0.39	1.34	1.75	0.14	0.06	0.25	50.73	18	37	27	61	484	490	bdl	270	76	1.4
KDT2-008	13.83	29.00	0.85	0.35	0.78	1.67	0.15	0.08	0.14	53.03	14	92	31	47	496	154	69	281	53	1.3
KDT2-009	15.98	35.73	0.34	0.45	0.83	1.76	0.20	0.10	0.57	43.80	73	118	39	57	555	1097	85	337	2	1.9
KDT2-010	15.77	33.18	0.51	0.37	1.24	1.89	0.21	0.11	0.42	46.11	62	83	30	94	549	673	bdl	401	76	1.7
KDT2-011	14.28	33.06	0.36	0.42	0.54	1.66	0.17	0.09	0.86	48.31	129	117	37	40	485	1219	35	288	79	1.6
KDT2-012	14.53	30.77	0.64	0.50	0.65	1.58	0.18	0.12	0.35	50.49	118	148	39	35	479	512	46	421	113	1.4
KDT2-013	15.01	35.25	0.63	0.39	0.68	1.78	0.19	0.09	0.33	45.47	19	49	32	53	523	448	80	263	58	1.8
KDT2-014	14.76	28.06	0.57	0.40	1.68	1.76	0.19	0.10	0.58	51.67	88	102	31	124	485	1149	55	336	115	1.3
KDT2-015	15.71	34.40	0.63	0.45	0.75	1.85	0.19	0.09	0.35	45.42	39	72	35	60	540	544	43	79	57	1.8
KDT2-016	14.65	34.13	0.37	0.62	0.75	1.49	0.19	0.08	1.37	45.92	50	103	51	42	575	2442	34	828	11	1.7
KDT2-017	14.26	33.57	0.33	0.40	0.50	1.76	0.19	0.10	0.85	47.77	107	97	38	49	540	1281	64	339	141	1.7
KDT2-018	15.31	33.81	0.31	0.34	0.58	1.96	0.23	0.13	0.42	46.72	94	48	32	44	617	620	37	272	127	1.7
KDT2-019	16.88	36.09	0.26	0.46	0.72	1.92	0.24	0.15	0.85	42.14	112	110	46	57	662	1391	28	493	50	2.0
KDT2-020	14.21	33.15	0.34	0.43	0.56	1.82	0.19	0.10	0.97	47.93	114	121	38	50	544	1451	96	462	78	1.6
KDT2-021	14.24	33.72	0.53	0.58	0.83	1.74	0.17	0.10	0.39	47.52	94	115	51	52	574	563	26	404	66	1.7
KDT2-022	13.75	29.95	0.80	0.26	2.42	1.74	0.16	0.08	0.30	50.35	95	105	18	183	542	709	37	195	16	1.4
KDT2-023	13.63	30.42	0.80	0.25	2.14	1.79	0.14	0.06	0.30	50.28	106	116	24	161	535	755	32	142	33	1.4
KDT2-024	14.70	27.42	0.80	0.35	1.34	1.97	0.19	0.11	0.64	52.22	44	89	22	100	514	1329	34	382	21	1.2

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
KDT2-025	11.07	27.48	0.55	0.43	2.42	1.36	0.18	0.11	0.12	56.17	16	15	44	232	476	221	bdl	126	68	1.2
KDT2-026	13.26	34.40	0.24	0.35	1.11	1.52	0.17	0.09	0.51	48.13	111	93	28	98	607	1024	22	89	bdl	1.7
KDT2-027	13.38	34.41	0.15	0.24	0.59	1.42	0.17	0.09	0.65	48.65	30	63	19	21	640	1185	65	496	1	1.7
KDT2-028	14.40	29.81	0.35	0.45	1.20	1.62	0.18	0.10	0.14	51.63	bdl	79	42	93	537	224	bdl	70	34	1.4
KDT2-029	13.56	32.91	0.50	0.34	1.69	1.82	0.13	0.07	0.37	48.44	89	104	24	117	541	628	42	114	17	1.6
KDT2-030	13.39	32.25	0.72	0.28	0.96	1.59	0.17	0.09	0.17	50.29	91	126	24	79	455	249	69	15	bdl	1.5
KDT2-031	13.04	30.89	0.57	0.34	0.85	1.17	0.13	0.07	0.88	51.75	30	75	36	49	504	1945	45	379	2	1.4
KDT2-032	16.11	37.72	0.45	0.47	2.23	1.83	0.19	0.11	0.32	40.41	57	103	38	173	614	527	bdl	6	5	2.2
KDT2-033	14.46	34.78	0.39	0.50	0.39	1.54	0.19	0.11	0.54	46.87	105	116	40	38	571	1121	60	244	bdl	1.8
KDT2-034	15.73	35.38	0.19	0.43	1.01	1.34	0.20	0.11	0.34	45.10	81	79	33	59	644	603	34	153	31	1.9
KDT2-035	14.59	36.99	0.22	0.31	0.88	1.95	0.20	0.13	0.21	44.41	60	30	bdl	bdl	645	291	bdl	52	bdl	2.0
KDT2-036	13.07	38.48	0.19	0.80	0.81	0.57	0.18	0.10	0.31	45.30	91	78	61	56	617	874	24	149	bdl	2.0
KDT2-037	14.73	35.56	0.12	0.65	0.35	0.83	0.16	0.08	0.86	46.32	109	116	49	39	522	1884	51	494	bdl	1.8
KDT2-038	13.69	43.24	0.15	0.45	0.60	1.19	0.23	0.09	0.44	39.74	43	21	43	41	722	869	41	115	2	2.6
KDT2-039	16.86	35.71	0.16	0.43	0.83	1.46	0.21	0.15	0.23	43.80	115	107	36	55	691	496	4	201	bdl	1.9
KDT2-040	15.58	35.81	0.19	0.68	0.70	1.11	0.24	0.11	0.38	44.98	bdl	bdl	48	54	739	816	32	574	27	1.9
KDT2-041	17.51	37.87	0.13	0.31	0.32	1.50	0.22	0.17	0.21	41.62	83	87	31	28	679	361	bdl	168	33	2.2
KDT2-042	14.62	39.11	0.24	0.55	1.18	1.18	0.25	0.15	0.19	42.40	bdl	29	48	61	718	344	bdl	154	bdl	2.2
KDT2-043	13.69	38.99	0.12	0.38	1.00	0.97	0.22	0.08	0.54	43.77	85	93	36	52	701	1086	9	342	bdl	2.1
KDT2-044	15.69	36.61	0.20	0.49	1.96	1.85	0.22	0.13	0.34	42.33	94	81	43	101	688	732	bdl	156	bdl	2.1
KDT2-045	14.85	38.83	0.20	0.57	0.89	1.22	0.19	0.15	0.77	42.00	118	87	44	49	632	1857	2	470	bdl	2.2
KDT2-046	14.94	36.07	0.20	0.36	1.18	1.65	0.20	0.12	0.22	44.92	76	110	23	98	583	414	14	129	30	1.9
KDT2-047	14.70	35.31	0.23	0.43	1.83	1.66	0.21	0.12	0.25	45.08	33	59	31	143	648	530	13	219	69	1.9
Mean	14.53	33.94	0.41	0.43	1.04	1.57	0.19	0.11	0.45	47.12	73	88	36	73	577	838	-	255	-	1.7
SD%	1.1	3.5	0.2	0.1	0.6	0.3	0.0	0.0	0.3	3.8	37.2	32.7	11.3	46.4	76.0	514.7	-	171.4	-	0.3
CV%	8	10	53	27	54	20	14	23	59	8	51	37	31	63	13	61	-	67	-	18

Khao Din Tai 3

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
KDT3-001	14.35	39.45	0.41	0.48	1.59	1.15	0.19	0.14	0.77	41.16	110	118	26	103	539	1651	38	562	bdl	2.2
KDT3-002	15.31	37.36	0.26	0.50	1.81	1.27	0.19	0.08	1.34	41.46	71	85	23	108	510	2599	bdl	806	19	2.1
KDT3-003	15.71	36.39	0.28	0.76	1.12	1.19	0.20	0.16	0.86	43.03	24	50	46	47	551	1994	bdl	428	bdl	2.0
KDT3-004	15.26	43.36	0.51	0.94	2.14	1.28	0.16	0.10	0.66	35.34	bdl	25	65	76	526	1476	34	319	bdl	2.9
KDT3-005	14.44	38.32	0.21	0.63	1.21	1.11	0.18	0.11	0.80	42.69	68	94	36	103	609	1653	20	515	1	2.1
Mean	15.01	38.98	0.34	0.66	1.57	1.20	0.18	0.12	0.88	40.73	60	74	39	88	547	1875	25	526	-	2.3
SD%	0.6	2.7	0.1	0.2	0.4	0.1	0.0	0.0	0.3	3.1	36.4	36.8	16.9	25.7	38.0	446.5	9.5	181.7	-	0.4
CV%	4	7	37	29	27	6	7	26	30	8	61	50	43	29	7	24	37	35	-	16

Ban Kruat 5

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
BKT5-001	15.36	41.33	0.13	0.58	1.00	0.95	0.20	0.16	1.55	38.24	24	51	49	61	721	3242	20	661	bdl	2.5
BKT5-002	15.78	34.21	0.32	0.80	1.59	1.32	0.17	0.13	0.56	44.85	124	114	54	73	618	1406	77	357	bdl	1.8
BKT5-003	14.07	42.50	0.16	0.62	0.99	0.70	0.16	0.10	2.37	37.62	bdl	33	56	50	591	5318	29	1122	bdl	2.5
BKT5-004	14.13	36.10	0.21	0.53	1.09	0.89	0.20	0.14	0.54	45.95	105	116	50	69	622	990	4	310	25	1.9
BKT5-005	12.68	31.84	0.69	0.37	0.99	1.36	0.13	0.08	0.60	50.97	118	177	35	45	550	1528	69	452	19	1.5
BKT5-006	14.61	33.12	0.25	0.43	1.25	0.95	0.15	0.10	0.84	47.99	96	120	34	79	536	1873	58	381	bdl	1.6
BKT5-007	14.92	33.52	0.27	0.38	1.00	1.10	0.17	0.10	0.85	47.36	6	79	36	61	569	1861	bdl	501	4	1.7
Mean	14.51	36.09	0.29	0.53	1.13	1.04	0.17	0.12	1.04	44.71	68	99	45	63	601	2317	37	541	-	1.9
SD%	1.0	4.2	0.2	0.2	0.2	0.2	0.0	0.0	0.7	5.0	53.7	48.5	9.5	12.3	62.2	1498.9	30.5	281.3	-	0.4
CV%	7	12	64	29	20	23	14	25	65	11	78	49	21	20	10	65	82	52	-	22

Ban Sai Tho8 Mound 1

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
STH8-001	13.71	40.39	0.12	0.42	0.72	0.42	0.19	0.06	0.11	43.77	70	38	35	32	516	194	bdl	bdl	bdl	2.2
STH8-002	15.19	38.19	0.21	0.72	0.41	0.47	0.22	0.13	1.25	42.81	89	61	59	24	757	2186	bdl	900	39	2.1
STH8-003	13.83	40.62	0.23	0.60	2.20	0.46	0.18	0.11	0.36	41.14	104	75	73	90	642	1000	bdl	610	80	2.3
STH8-004	15.11	42.59	0.27	0.62	1.94	0.50	0.25	0.05	0.29	38.23	63	58	36	50	672	430	bdl	118	bdl	2.6
STH8-005	13.29	36.66	0.09	0.34	0.88	0.44	0.21	0.05	0.05	47.91	99	78	21	37	503	86	bdl	bdl	bdl	1.8
STH8-006	13.60	35.71	0.10	0.45	1.06	0.41	0.10	0.06	0.66	47.63	70	86	55	52	362	1364	16	160	31	1.8
STH8-007	13.89	34.42	0.13	0.53	1.04	0.40	0.18	0.08	0.22	48.95	111	99	47	30	516	538	bdl	419	bdl	1.7
Mean	14.09	38.37	0.16	0.52	1.18	0.44	0.19	0.08	0.42	44.35	87	71	46	45	567	828		349		2.1
SD%	0.7	3.0	0.1	0.1	0.7	0.0	0.0	0.0	0.4	4.0	19.2	20.0	17.4	22.2	131.8	747.9		308.9		0.3
CV%	5	8	43	25	55	8	25	40	98	9	22	28	37	50	23	90		89		17

Ban Sai Tho8/2 Mound 6

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
STH8/2-001	14.08	38.31	0.13	0.47	0.85	0.65	0.25	0.10	0.36	44.60	150	94	36	45	523	800	bdl	265	36	2.0
STH8/2-002	14.27	36.02	0.08	0.44	2.25	0.41	0.22	0.08	0.19	45.92	140	83	31	47	423	279	bdl	222	18	1.9
STH8/2-003	13.79	38.21	0.08	0.33	0.69	0.37	0.16	0.08	0.10	46.07	120	77	29	24	393	445	bdl	75	bdl	2.0
STH8/2-004	14.06	35.15	0.08	0.47	0.86	0.38	0.16	0.06	0.05	48.63	104	bdl	56	50	339	245	bdl	72	bdl	1.7
STH8/2-005	15.23	38.17	0.10	0.50	0.55	0.40	0.23	0.10	0.09	44.56	76	46	66	26	393	87	bdl	56	bdl	2.0
STH8/2-006	13.38	33.45	0.08	0.60	1.72	0.40	0.19	0.08	0.08	49.93	69	25	56	73	397	260	bdl	114	42	1.6
STH8/2-007	14.77	35.38	0.10	0.43	0.60	0.37	0.21	0.07	0.06	47.94	131	73	45	45	341	78	bdl	60	bdl	1.8
Mean	14.22	36.38	0.09	0.46	1.08	0.43	0.20	0.08	0.13	46.81	113	61	46	44	401	314	-	123	-	1.9
SD%	0.6	1.9	0.0	0.1	0.7	0.1	0.0	0.0	0.1	2.1	31.2	28.2	14.5	16.3	61.8	248.3	-	84.9	-	0.2
CV%	4	5	19	18	61	24	17	18	84	4	28	46	32	37	15	79	-	69	-	9

Ban Sai Tho10 South

Sample	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	Rb_2O	SrO	ZrO_2	BaO	La_2O_3	CeO_2	Nd_2O_3	RII
	wt%										ppm									%
STH10-001	12.41	31.72	0.09	0.21	0.32	0.44	0.19	0.05	0.05	54.44	114	86	12	20	450	188	56	48	bdl	1.4
STH10-002	14.41	35.89	0.08	0.41	0.24	0.41	0.20	0.06	0.09	48.11	103	96	18	11	504	169	3	121	bdl	1.8
STH10-003	13.36	39.83	0.06	0.34	0.32	0.39	0.23	0.07	0.07	45.26	94	76	21	19	395	192	6	25	bdl	2.1
STH10-004	14.14	34.26	0.07	0.32	0.47	0.48	0.22	0.06	0.06	49.84	18	bdl	bdl	bdl	570	198	bdl	95	bdl	1.6
STH10-005	13.96	37.23	0.07	0.29	0.31	0.47	0.23	0.06	0.07	47.21	32	27	20	15	628	132	51	77	bdl	1.9
STH10-006	11.39	37.79	0.20	0.35	0.72	0.46	0.21	0.05	0.10	48.59	29	13	33	20	670	388	48	151	bdl	1.9
STH10-007	13.42	35.65	0.09	0.31	0.55	0.48	0.23	0.06	0.05	49.07	12	23	22	27	537	264	bdl	42	bdl	1.7
Mean	13.30	36.05	0.09	0.32	0.42	0.45	0.22	0.06	0.07	48.93	57	48	20	18	536	219	24	80	-	1.8
SD%	1.1	2.6	0.0	0.1	0.2	0.0	0.0	0.0	0.0	2.8	44.2	36.7	7.2	6.0	96.6	84.4	25.7	45.3	-	0.2
CV%	8	7	51	19	41	8	8	13	23	6	77	77	36	34	18	39	105	57	-	12

Appendix K Selected materials and oxides used in the materials balance calculations

Selected materials and oxides used in producing Figure 8.88

Material	SiO_2	TiO_2	Al_2O_3	ZrO_2	K_2O	Rb_2O	MgO	CaO	SrO	BaO	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	P_2O_5
Mean ore	24.18	1.39	14.47	390	0.10	19	0.27	0.14	14	251	0.17	0.09	0.18	57.97	15	455	0.92
Mean technical ceramics	84.36	0.48	11.79	917	0.11	30	0.23	0.42	52	634	0.01	0.05	0.06	2.24	8	37	0.08
Mean slag	32.83	1.75	14.85	539	0.44	37	0.39	0.83	57	932	0.19	0.10	0.58	47.38	75	94	0.50
Modelled slag	32.20	1.43	15.48	476	0.11	21	0.29	0.18	19	311	0.17	0.09	0.19	57.62	16	455	0.92
Absolute error	0.63	0.33	-0.63	63	0.32	15	0.10	0.65	38.63	622	0.02	0.01	0.39	-10.24	59	-361	-0.42
Relative error	2	23	-4	13	284	72	35	364	205	200	10	8	208	-18	368	-79	-46

Notes: Ore: KDT2e001 and KDT2e002 (see Table 8.3 and 8.4), Technical ceramics: KDT2FF001 and KDT2FF002 (see Table 8.6 and 8.7), and Slag: KDT2-007 to KDT2-021 (see Table 8.9-8.12 and Appendix J)

Selected materials and oxides used in producing Figure 8.89

Material	SiO_2	TiO_2	Al_2O_3	ZrO_2	K_2O	Rb_2O	MgO	CaO	SrO	BaO	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	P_2O_5
Mean ore	24.18	1.39	14.47	390	0.10	19	0.27	0.14	14	251	0.17	0.09	0.18	57.97	15	455	0.92
Mean technical ceramics	83.75	0.53	11.98	825	0.16	33	0.26	0.33	39	592	0.02	0.03	0.11	2.56	24	28	0.12
Mean slag	34.76	1.54	14.26	577	0.43	36	0.42	1.07	75	829	0.18	0.10	0.44	46.22	72	86	0.41
Modelled slag	34.76	1.27	14.26	470	0.11	21	0.27	0.17	18	313	0.15	0.08	0.17	49.34	17	389	0.80
Absolute error	0.00	0.28	0.00	106	0.31	15	0.15	0.89	58	516	0.04	0.02	0.27	-3.12	54	-303	-0.39
Relative error	0	22	0	23	274	69	55	517	309	165	24	29	152	-6	316	-78	-49

Notes: Ore: KDT2e001 and KDT2e002 (see Table 8.3 and 8.4), Technical ceramics: all analysed (see Table 8.6 and 8.7), and Slag: all analysed excluding slb-KDT2 (see Table 8.9-8.12 and Appendix J)

Selected materials and oxides used in producing Figure 8.90

Material	SiO_2	TiO_2	Al_2O_3	ZrO_2	K_2O	Rb_2O	MgO	CaO	SrO	BaO	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	P_2O_5
Mean ore	38.84	0.36	10.98	534	0.07	16	0.11	0.27	15	979	0.14	0.04	0.38	48.37	151	60	0.26
Mean technical ceramics	83.52	0.52	13.61	942	0.16	21	0.13	0.14	13	429	0.01	0.02	0.01	1.63	10	5	0.10
Mean slag	38.24	0.44	14.04	565	0.52	46	0.37	1.17	45	825	0.19	0.08	0.42	44.20	86	70	0.16
Modelled slag	40.76	0.38	11.52	561	0.07	17	0.12	0.28	16	1026	0.15	0.05	0.40	50.66	158	63	0.27
Absolute error	-2.52	0.06	2.52	4	0.45	29	0.25	0.90	28.64	-201	0.04	0.03	0.02	-6.46	-72	8	-0.11
Relative error	-6	17	22	1	665	176	212	322	178	-20	25	69	6	-13	-46	12	-40

Notes: Ore: STH8e001 to STH8e006 (see Table 8.3 and 8.4), Technical ceramics: STH8M1CP and STH8M1FF (see Table 8.6 and 8.7), and Slag: STH8-001 to STH8-007 (see Table 8.9-8.12 and Appendix J)

Selected materials and oxides used in producing Figure 8.91

Material	SiO_2	TiO_2	Al_2O_3	ZrO_2	K_2O	Rb_2O	MgO	CaO	SrO	BaO	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	P_2O_5
Mean ore	22.68	0.32	9.89	324	0.05	13	0.18	0.52	19	83	0.18	0.05	0.04	65.78	162	73	0.24
Mean technical ceramics	83.52	0.52	13.61	942	0.16	21	0.13	0.14	13	429	0.01	0.02	0.01	1.63	10	5	0.10
Mean slag	38.24	0.44	14.04	565	0.52	46	0.37	1.17	45	825	0.19	0.08	0.42	44.20	86	70	0.16
Modelled slag	38.26	0.46	14.02	517	0.08	19	0.24	0.66	26	155	0.22	0.07	0.05	82.86	205	92	0.32
Absolute error	-0.02	-0.02	0.02	48	0.44	28	0.13	0.51	18.72	670	-0.03	0.01	0.37	-38.66	-119	-22	-0.15
Relative error	0	-5	0	9	544	149	56	77	72	433	-16	13	683	-47	-58	-24	-49

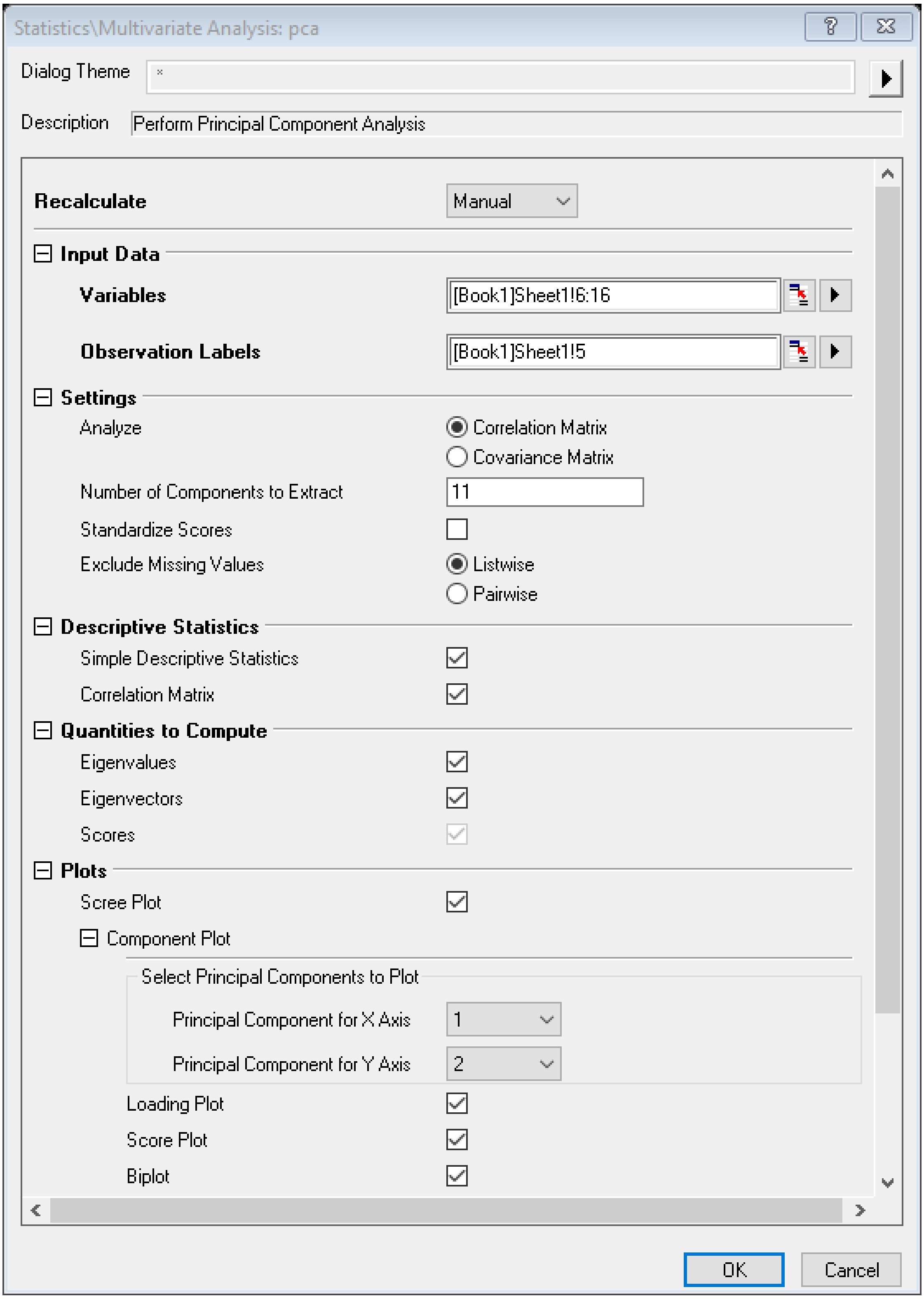
Notes: Ore: STH8e002 and 004 (see Table 8.3 and 8.4), Technical ceramics: STH8M1CP and STH8M1FF (see Table 8.6 and 8.7), and Slag: STH8-001 to STH8-007 (see Table 8.9-8.12 and Appendix J)

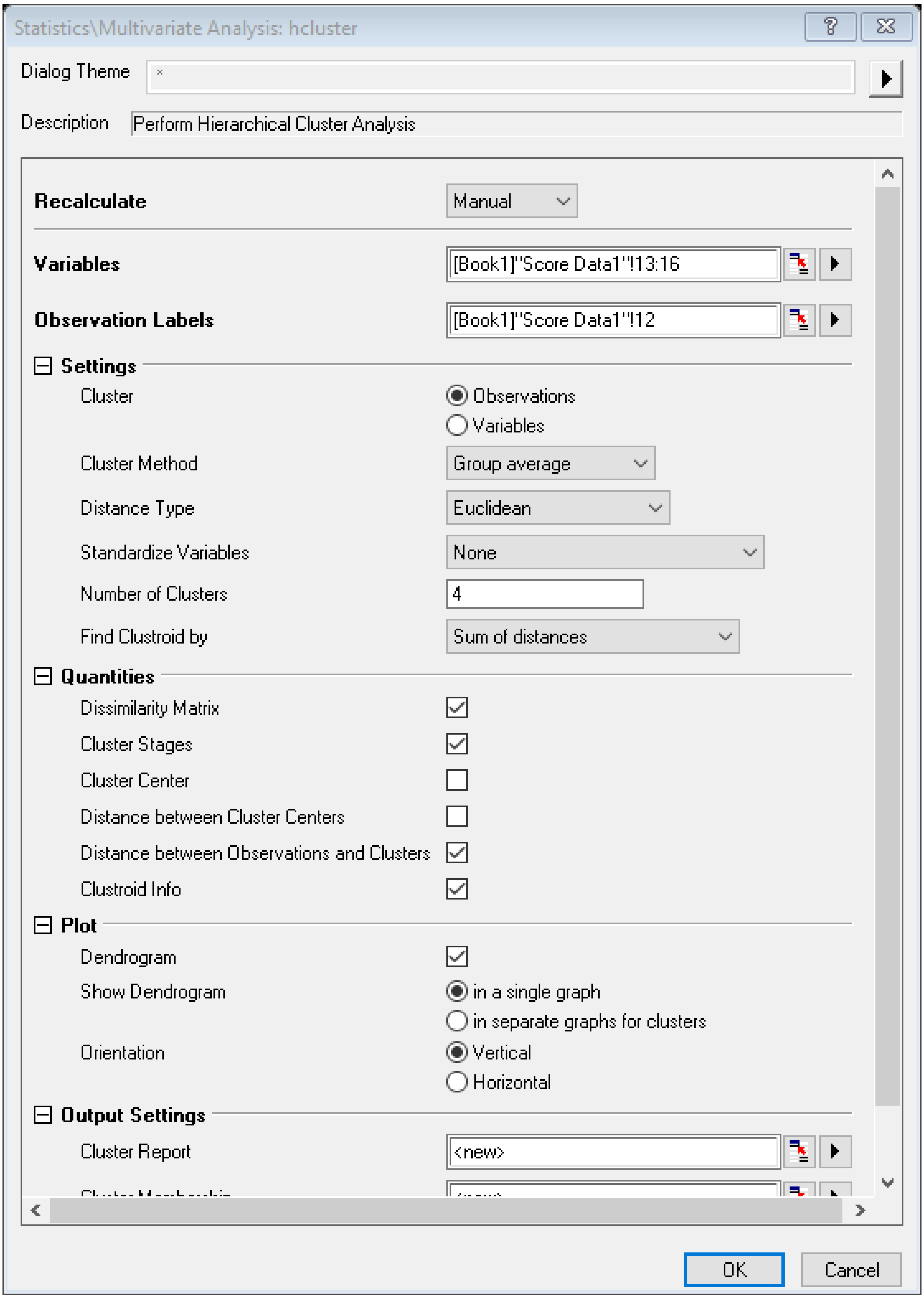
Selected materials and oxides used in producing Figure 8.92

Material	SiO_2	TiO_2	Al_2O_3	ZrO_2	K_2O	Rb_2O	MgO	CaO	SrO	BaO	V_2O_5	Cr_2O_3	MnO	FeO	CuO	ZnO	P_2O_5
Mean ore	13.44	0.32	8.46	308	0.03	13	0.30	0.94	33	89	0.22	0.04	0.01	75.97	117	58	0.26
Mean technical ceramics	83.52	0.52	13.61	942	0.16	21	0.13	0.14	13	429	0.01	0.02	0.01	1.63	10	5	0.10
Mean slag	38.24	0.44	14.04	565	0.52	46	0.37	1.17	45	825	0.19	0.08	0.42	44.20	86	70	0.16
Modelled slag	38.32	0.53	13.95	625	0.08	21	0.40	1.19	44	221	0.28	0.06	0.02	93.87	146	73	0.35
Absolute error	-0.09	-0.09	0.09	-60	0.44	25	-0.03	-0.02	1.23	603	-0.09	0.02	0.40	-49.67	-60	-3	-0.18
Relative error	0	-17	1	-10	567	116	-7	-2	3	272	-32	34	2107	-53	-41	-4	-53

Notes: Ore: STH8e004 (see Table 8.3 and 8.4), Technical ceramics: STH8M1CP and STH8M1FF (see Table 8.6 and 8.7), and Slag: STH8-001 to STH8-007 (see Table 8.9-8.12 and Appendix J)

Appendix L The settings in the PCA and Hierarchical Cluster Analysis on OriginPro 2015

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Description
Perform Hierarchical Cluster Analysis
Recalculate
Manual
Variables
[Book1]"Score Data1"!13:16
Observation Labels
[Book1]"Score Data1"!12
Settings
Cluster
Observations
Variables
Cluster Method
Group average
Distance Type
Euclidean
Standardize Variables
None
Number of Clusters
4
Find Clustroid by
Sum of distances
Quantities
Dissimilarity Matrix
Cluster Stages
Cluster Center
Distance between Cluster Centers
Distance between Observations and Clusters
Clustroid Info
Plot
Dendrogram
Show Dendrogram
in a single graph
in separate graphs for clusters
Orientation
Vertical
Horizontal
Output Settings
Cluster Report
<new>
OK
Cancel